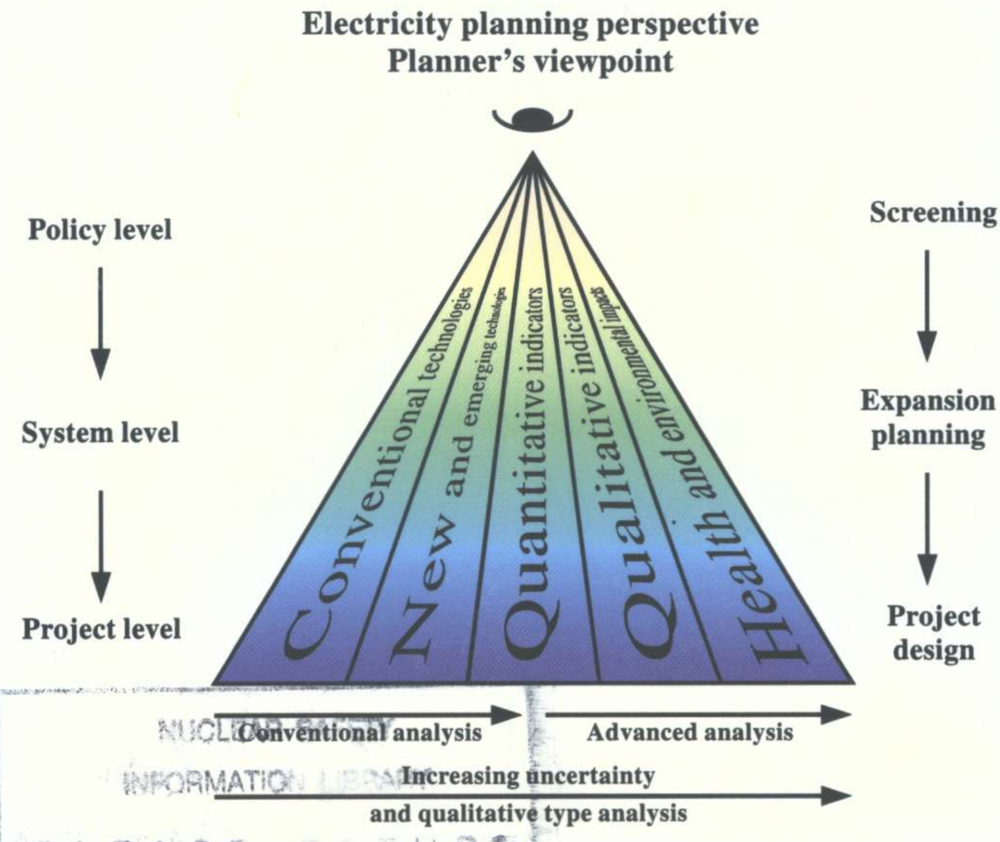
Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making



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Vienna, 16–19 October 1995

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The cover shows the electricity planner's perspective which can be viewed as a pyramid.

The different levels of the planning process are represented vertically. Ever more detailed information analyses are required as the planner moves from top to bottom. First, at the **policy level**, general characteristic data and analysis provide decision makers with a broad understanding of the options available, giving the pros and cons of economic, health and environmental aspects of various electric power technologies and associated policies. Second, the **system level** requires a more detailed understanding of electric power systems, forecasting the rate of growth in electricity demand to meet capacity expansion requirements with different fuel options and generating plant candidates. Analyses at this level include traditional least cost planning techniques, and methods of evaluating the health, environmental and social costs resulting from selected expansion strategies. Third, at the **project level**, analyses are highly specific, calling for ever more detailed data on project costs, emissions and other burdens resulting from plant construction and operation. This final analysis must be aligned with policy and system levels, otherwise there is the risk of failing to account for broad policy issues and their impact on existing and future power plants in the total system.

Horizontally, each level represents the increasing complexity, comprehensiveness of analysis, and degree of uncertainty in the information provided. The available technologies range from proven technologies, e.g. fossil fuel and nuclear energy systems, to state of the art, new and emerging technologies, e.g. clean coal technologies, advanced nuclear power plants and renewable energy systems under development. The parameters related to health and environmental aspects range from quantitative information on emissions to qualitative effects on landscape, quality of life and so on. The complexity of the analysis ranges from conventional methods for cost comparisons to more advanced methods such as multicriteria techniques for incorporating quantitative and qualitative environmental indicators.

ELECTRICITY, HEALTH AND THE ENVIRONMENT: COMPARATIVE ASSESSMENT IN SUPPORT OF DECISION MAKING

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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IN SUPPORT OF DECISION MAKING
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FOREWORD

The Symposium on Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making, was held from 16 to 19 October 1995 at the IAEA Headquarters in Vienna. It was organized jointly by the IAEA and nine other international organizations — the European Commission (EC), the Economic and Social Commission for Asia and the Pacific (ESCAP), the International Institute for Applied Systems Analysis (IIASA), the Nuclear Energy Agency of the OECD (OECD/NEA), the Organization of Petroleum Exporting Countries (OPEC), the United Nations Environment Programme (UNEP), the United Nations Industrial Development Organization (UNIDO), the World Bank/International Bank for Reconstruction and Development (IBRD) and the World Meteorological Organization (WMO). About 200 experts from 53 countries and 16 different organizations took part.

The Symposium was convened as part of the inter-agency joint project on databases and methodologies for comparative assessment of different energy sources for electricity generation (DECADES). It was opened with an address by Dr. Hans Blix, Director General of the IAEA, followed by opening statements from the EC, IBRD, UNEP, UNIDO, WMO and the Chairman of the DECADES Project Steering Committee, Mr. B.A. Semenov (Deputy Director General of the IAEA).

The main objective of the Symposium was to enhance and strengthen information sharing and co-operation between interested and affected parties in the field of electricity demand analysis and supply planning, aiming at implementing sustainable policies in the power sector, taking into account economic, social, health and environmental aspects. To meet this objective, the Symposium sessions addressed the following topics: key issues in the decision making process; assessment of health and environmental impacts; integrated framework for comparative assessment; implementation of comparative assessment; country case studies; and comparative assessment in decision making. A closing round table focused on challenges for international co-operation aiming at implementation of sustainable electricity policies. In addition to the main sessions, poster presentations illustrated results from comparative assessment studies carried out in different countries, and software demonstrations provided opportunities for participants to gain information about state of the art computer tools, databases and analytical models that are available for use in decision support studies.

The first technical session of the Symposium set the stage by highlighting the key issues to be addressed for implementing sustainable electricity policies in developing countries, countries in transition and industrialized countries. Session 2 focused on the assessment of health and environmental impacts of different energy systems. Session 3 dealt with the formulation of integrated frameworks for comparative assessment in the context of analysing local, regional and global issues.

Sessions 4 and 5 reviewed the experience that had been obtained on the implementation of comparative assessment in various projects and reported results from a number of comparative assessment case studies that had been carried out in different countries and organizations using various tools. In the final technical session, the experience with implementing comparative assessment as an integral part of the decision making process was reported in four papers.

The closing round table discussed the main issues that emerged during the Symposium, which were highlighted by the rapporteurs for the respective sessions. Active discussions with the participants allowed the organizers of the Symposium to draw some main findings and conclusions, as well as to provide some recommendations for follow-up actions that could be undertaken in the framework of the DECADES project.

The IAEA wishes to acknowledge the support of the sponsoring organizations, the valuable contributions of the authors and presenters of papers, posters or software demonstrations, chairpersons and scientific secretaries, as well as the assistance and efforts of the Programme Committee.

EDITORIAL NOTE

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TOWARDS SUSTAINABLE ELECTRICITY POLICIES
Challenges for International Co-operation
(Summary of Round Table)

OPENING SESSION

Chairman

H. BLIX
IAEA

OPENING STATEMENT

H. Blix
Director General,
International Atomic Energy Agency,
Vienna

I welcome you all to this international Symposium, which addresses some topics of great concern to decision makers who have to devise policies for sustainable energy production and electricity generation. The Symposium will examine the economic, health and environmental aspects of different energy sources, and it will consider how the presently available methodologies and tools for comparative assessment could be adapted better to provide the types of information needed by decision makers.

I am pleased that the IAEA is hosting this Symposium, but I want to stress that it is a co-operative effort by the ten sponsoring organizations. The broad sponsorship of and the wide participation in the Symposium show that the subject matter is high on the agenda of analysts and policy makers.

As an introduction, I would like to share with you some thoughts on the opportunities and challenges for the power sector, from my perspective, and also briefly describe the IAEA's activities in the field of comparative assessment.

I start from several basic premises, which may not be shared by all:

— Energy use will grow significantly, especially in developing countries. Continued improvements in efficiency of energy production and use will be very important, but will by no means offset the strong growth in demand. For example, a study by China's State Science and Technology Commission estimates that by the middle of the next century the country's total energy demand will be some 4000 to 5000 million tonnes of coal equivalent, or about four times today's demand. This means that in 50 years' time China's energy demand will be nearly as great as the present total energy demand of all OECD countries (including the United Sates of America), which is some 6500 million tonnes of coal equivalent.

— Fossil fuels now dominate the global energy supply, and this domination can be expected to continue. For example, over the next two decades India plans to treble, and China to double, the consumption of coal for electricity generation. A growing global consumption of fossil fuels is viewed as increasingly problematic, for environmental reasons, notably the risk of global warming that is linked to the increasing emissions of greenhouse gases, especially CO_2, from the burning of fossil fuels.

— Solar power, wind power, biomass and other renewables (other than conventional, large scale hydropower) will bring a valuable, but minor, contribution to the global energy supply in the coming decades. The views expressed in one of the response strategies devised by the Intergovernmental Panel on Climate Change (IPCC) for reducing the risk of global warming, arguing that renewable energy could cover some 80% — and biomass some 50% — of the world's energy needs a hundred years from now, is viewed as completely unrealistic by many — and I think most — experts.
— Nuclear fusion, as a practical source of energy, is viewed as very distant. If the world were looking for an existing, nearly economically viable technology for an almost inexhaustible electricity supply, it could have it in breeder reactors — of which several are in operation. However, while the world has been living for decades with vast quantities of plutonium ready to be exploded in bombs, it seems reluctant to accept plutonium as a fuel for electricity generation.
— Expansion of nuclear power, which now provides about 7% of the world's commercial energy and 17% of its electricity, could provide at least an important part of the solution to the problem of increasing energy supply without increasing emissions. Nuclear energy contributes practically no CO_2, SO_2 or NO_x emissions. It is already today of significance in helping us to limit emissions into the atmosphere. If the approximately 430 nuclear power reactors operating today were replaced by coal fuelled plants, there would be an increase of more than 8% in the global CO_2 emissions from energy use.
— However, a broad sector of the public in many countries — especially industrialized ones — is hesitant or opposed to an increased use of nuclear power, or even a continuation at present levels. Mainly three factors prompt these attitudes: fear of accidents, fear of long lived radioactive wastes and fear that use of nuclear power might contribute to proliferation of nuclear weapons. The last point is probably the least important. The expansion of nuclear power has not led to proliferation of nuclear weapons. Rather, we have seen a continuous increase in the number of countries committing themselves to non-proliferation. This factor and accelerating nuclear disarmament will probably reduce the link between nuclear weapons and nuclear power in the public's mind.
— In general, environmentalist groups are adamantly opposed to nuclear power and urge more vigorous efforts for energy conservation, the development and greater use of renewables, and new lifestyles as means to respond to the threat of global warming. However, there are examples of different opinions among responsible and uncommitted organizations, such as the Club of Rome, which a few years ago came to the conclusion that the use of fossil fuels is probably more dangerous to society — because of the CO_2 they produce — than nuclear energy.

In the face of these contradictory premises, it will be a major challenge for the energy sector and especially for the electric power sector — in both industrialized and developing countries — to get public acceptance for any policy ensuring sustainable and adequate energy supplies. For a time, and in some countries, one can try to postpone decisions in the hope that they will be less difficult later. If there is a need for more electricity, however, this option may not be available. When this need is pressing today, the decision in industrialized countries often is greater reliance on natural gas on the grounds that it is economically viable, and that it appears to be environmentally attractive since the CO_2 emissions from gas are about half those from coal, per unit of energy produced. However, the leakages of methane from gas extraction sites and gas pipelines are of the order of 5-10%, which more than offsets the gains from the lower CO_2 emissions.

The threat of global climate change is high on the agenda of Governments, but we have to note that — three years after the Rio 'Earth Summit' which set ambitious targets for sustainable development — the progress made worldwide, for example in reducing greenhouse gas emissions, is extremely small, not to say negligible. Carbon dioxide emissions have slowed only marginally in industrialized countries — mainly because of the recent economic recession — and have continued to increase significantly in most developing countries, owing to energy demand growth and reliance on fossil fuels as the most readily available energy source.

Indeed, 'sustainable development' in the field of energy seems to have quite different meanings in different regions and fora, and to be difficult to put into practice. The first Conference of Parties to the Framework Convention on Climate Change, which was held in Berlin at the end of March 1995, showed that reaching an international consensus on reducing greenhouse gas emissions will take some time.

The medium term outlook does not seem to be better. In particular, the expected continued dramatic growth in energy and electricity consumption in Asia will lead to a drastic increase in greenhouse gas emissions if measures are not taken soon to reduce the share of fossil fuels, especially coal, in electricity generation. In eastern Europe, energy consumption has flattened because of the economic stagnation that has occurred; however, as the economies of the region begin to recover and grow, these countries will also be faced with increases in emissions, unless effective control and mitigation measures are implemented. In western Europe too, according to the findings of a number of recent studies, CO_2 emissions will continue to grow after the turn of the century. The mothballing of nuclear programmes in some countries and the commissioning of new gas fired or coal fired power plants are the main causes of this trend. I cannot fail to add that the case of France, where more than 75% of electricity is produced by nuclear power, clearly demonstrates that nuclear power could play a major role in reducing CO_2, SO_2 and NO_x emissions, while enhancing the economic competitiveness of the industry.

Also, a study commissioned by the Institute of Energy Economics in Japan concluded that if CO_2 emissions are to be curbed to the 1990 levels, Japan will need between 160 and 300 GW(e) of nuclear power by the end of 2100. At present, Japan has 38 GW(e) of nuclear capacity.

I do not suggest that nuclear power alone can solve all of the problems involved in achieving a secure and sustainable energy supply worldwide. However, together with renewable sources and energy conservation, both of which are important, nuclear power could play a very significant role in strategies aiming towards this goal. The two cases I have just mentioned are good illustrations.

I am fully aware that the issues are fraught with emotional reactions and that Governments must pay attention to public opinion. However, it seems to me that if we have sincerely and scientifically identified some severe threats being caused by our present energy policies, we must assess and compare on a 'level playing field', i.e. rationally, all the available energy supply options — renewable, fossil and nuclear — taking into account their complete fuel cycles, their technical and economic performance, and their impact on health and the environment. This is the focus of the IAEA's programme on the comparative assessment of energy sources and also of the DECADES project within which this Symposium is organized.

Let me now give you some glimpses of the IAEA's activities in the field of comparative assessment of energy sources, in particular for electricity generation.

There is no single United Nations organization — or other worldwide intergovernmental organization — that covers comprehensively all the issues — including the social, health and environmental impacts — related to energy and electricity production and use. However, there are an increasing number of joint programmes of work which bring together the expertise and know-how of different international organizations.

The IAEA has a long tradition in the analysis and planning of energy and electricity systems. In response to requests from its Member States, the IAEA has implemented and disseminated energy and electricity system analysis models that are widely used by national institutes and other international organizations. Within the Technical Co-operation Programme of the IAEA, a large number of projects are devoted to supporting Member States in the field of energy and electricity system analysis and planning. These projects examine not only the nuclear power option but also fossil and renewable energy systems. The IAEA does by no means blindly counsel the use of nuclear power. Indeed, in many cases the nuclear option would be inappropriate.

While earlier it was considered that the "cheapest energy was the best energy" and accordingly the analysis of energy options did not have many dimensions, the increasing concern about the social, health and environmental impacts of energy production and use has led to a broadening of the analysis that is necessary. In order to assist in more comprehensive comparative assessments in the power sector, the IAEA has since the 1980s broadened the scope of its analytical activities to incorporate those concerns together with the traditional economic and technical comparisons. Moreover, a close co-operation on these matters has been established and maintained by the IAEA with other international organizations. The co-operation includes exchange of information, task sharing and joint activities in order to avoid duplication and to enhance the overall efficiency of the programmes carried out in the respective organizations as well as the quality and credibility of their results.

More recently, the IAEA programme has put increased emphasis on global climate change issues, especially on the potential role of nuclear power and other energy options in reducing greenhouse gas emissions. Contributions were provided to the Second Assessment Report of the IPCC. Our work in this field will continue in connection with the Framework Convention on Climate Change and with the ongoing work of the IPCC. In 1997–1998, the IAEA programme on comparative assessment of energy sources will be strengthened and redefined, building upon the results and outcomes of the current work. I trust that the presentations and discussions during this Symposium will provide concrete guidance on the priority issues that are to be addressed by the IAEA programme.

The present Symposium is one milestone in a continuing process of dialogue and exchange of views among experts from Member States and representatives from international organizations. It is a direct follow-up of the Senior Expert Symposium on Electricity and the Environment, which was jointly organized by the IAEA and ten other international organizations and held in Helsinki in May 1991. The Helsinki Symposium recommended inter alia that programmes of research on comparative assessment of electricity generation options and strategies should be undertaken, and stressed that international organizations having a mandate in this field should play a leading role and should co-operate to provide improved databases and methodologies for comparative assessment.

The DECADES project, which is carried out jointly by nine international organizations, was initiated by the IAEA in 1992 in response to the recommendations of the Helsinki Symposium and has led to the present meeting. The objectives of the DECADES project and its main results and outcomes will be presented to you later on, in particular by the chairman of the Steering Committee for the project, Mr. Semenov. At this stage, I would like only to point out that the co-operative framework that was adopted to carry out this project has helped to ensure that there is an objective and comprehensive assessment of all energy options for electricity generation.

Coming to key issues for decision makers in the power sector, I would like, first of all, to point out that an adequate electricity supply is a prerequisite for economic development and for enhancing social welfare. The positive aspects of electricity *use* should not be overlooked in the process of assessing the potential negative impacts of its *production*. For a number of developing countries that are experiencing under-supply of electricity and power cuts — which do have significant adverse economic impacts and also social, health and environmental effects — the priority will continue to be on adding electricity generation capacity at affordable costs. For those countries, comparative assessment includes assessing not only the potential negative impacts of different supply options but also the impacts of *non-supply*. You may recall that the famous Indian scientist Homi Bhabha coined the expression "no energy is more expensive than no energy".

According to estimates published by the International Energy Agency[1], electricity demand in developing regions of the world is projected to grow up to the year 2010 at a rate of about 5% per year, i.e. about twice as high as the rate in OECD countries. If this demand is met, it would mean that the electricity consumption per capita would almost double, from just under 700 kW·h per capita to around 1200 kW·h per capita. Even so, this would still be less than one sixth the electricity consumption per capita in OECD countries, and in some countries the levels would be far lower. This clearly indicates that further increase in generating capacity is inevitable.

A particular question is the impact of today's energy choices on tomorrow's world. Classical thermal power plants have typical lifetimes of some 30 years, nuclear power plants of the newest generation are expected to be in operation for around half a century and hydropower plants have even longer lifetimes. Heavy metals in the wastes arising from fossil fuel burning will remain toxic forever and some radioactive wastes have to be disposed of in repositories ensuring their isolation from the biosphere over many thousands of years. Increasing CO_2 concentrations in the atmosphere might entail irreversible global climate change. In view of these long term effects of energy choices, care must be taken to avoid energy policies and waste handling practices today that will lead to unacceptable effects for future generations.

In spite of the global attention that has been given to all aspects of energy supply systems, we still face major areas of uncertainty. The uncertainties surrounding global climate change issues illustrate this point. First, there is the uncertainty about the *amount* of climate change that might result from rising concentrations of greenhouse gases in the Earth's atmosphere. Secondly, there are difficulties in assessing and evaluating the overall social, health and environmental *impacts* of global climate change, if it were to occur, in a given country or region.

Let me emphasize that nuclear power is one of the few energy sources for which the risks and potential impacts have been recognized and dealt with from its very beginning. The effects of radiation exposure due to nuclear power production are much better known — and more strictly limited — than the effects of pollutants from other energy cycles. Furthermore, the costs of minimizing these impacts are largely internalized in nuclear power generation costs. For fossil fired power plants, the emissions of SO_2 and NO_x can be reduced — at a considerable cost — through

[1] Energy Policies of IEA Countries: 1994 Review, International Energy Agency, OECD, Paris (1995).

the installation of scrubbing devices. In this area, I may mention that the demonstration of electron beam accelerators as an advanced technique for flue-gas cleaning is being assisted by the IAEA through its technical co-operation programme.

Carbon dioxide emissions, however, cannot be controlled through economically viable methods, and the assessment of the potential cost of CO_2 emissions, as well as the finding of ways to include this cost in the prices paid by consumers are particularly difficult. Other potential impacts from fossil fuel burning, for example those due to toxic heavy metals in particulate emissions and solid wastes from coal burning, also are much less well known than the effects of radiation.

This points to the urgent need for further research in the field of impact assessment, for evaluation of external costs and for ways to include these externalities in the prices paid for energy and electricity.

Finally, I would like to stress the transboundary aspects of national power sector policies. While decisions about using or not using any given technology are and will remain the prerogative of each country, it should be recognized that these decisions can have significant impacts beyond the country's borders. Comparative assessment frameworks should allow analysis of transboundary impacts and reflect them in the choice of optimized strategies for electricity system expansion. In this connection, international organizations can play a key role in helping to build consensus on global priorities, which in turn will facilitate the implementation of sustainable strategies in different countries — reflecting both regional priorities and worldwide objectives.

The issues that I have pointed out in these introductory remarks certainly are not exhaustive, and I am sure that the experts participating in this Symposium will identify and elaborate on a number of other important issues and initiate a more comprehensive discussion on the challenges that decision makers will face in the coming years. This Symposium will not address or solve all the problems. However, I do hope that it will offer opportunities for a fruitful exchange of views between experts having a wide range of scientific backgrounds and representing different regions of the world. Moreover, I am convinced that the presentations and discussions will help to better understand the issues and to highlight ways and means for addressing them. The findings and recommendations from the Symposium should also identify areas where further work should be undertaken by international organizations and national research institutes, with a view to a broader use of comparative assessment as a part of the decision making process for the electric power sector.

The challenge remains to design approaches that incorporate all relevant elements into a comprehensive comparative assessment of different options and strategies, and to develop enhanced databases, analytical methodologies and other decision aiding tools upon which policy makers can rely to support their decisions. International organizations have an important role to play in helping to meet these challenges. In particular, internationally harmonized approaches — designed and agreed upon in a co-operative framework — may help to address transboundary issues, such as acid rain, and global issues, such as greenhouse gas emissions.

I trust that these points and other issues will be discussed thoroughly during this Symposium, and I look forward to the concrete outcomes, conclusions and findings that will result from the presentations and discussions that will take place.

OPENING STATEMENT

E. Andreta, P. Valette
Directorate General for Science, Research and Development (DG XII),
European Commission,
Brussels, Belgium

Technology, and in particular research and development (R&D), is playing a major role in the issue of electricity, health and the environment, but it would be wrong to focus only on technology. It is crucial to understand also the links between electricity and the rest of the energy system and between electricity, the environment and the economy. All decisions concerning the electricity sector have very important consequences on the above mentioned areas (energy–environment–economy, E3).

There are three key factors regarding future development:

— Electricity is at the heart of modern society; the services that it provides for households and for the productive sectors reflect and illustrate the progress of the society. Electricity is also the key factor in the economic development in developing countries; two billion people in these countries have no electric facilities — a situation that will have to be changed in the future.
— Environmental issues have to be taken into account and integrated in the design of any instrument and policy; they play a role at a local level and, as recognized more recently, also at a global level.
— The institutional aspects and the role of regulation/deregulation taking place in the ongoing liberalization of the energy market are other components that have emerged and that have to be considered because they have a strong impact on the functioning of the electricity system.

These three factors are crucial for the future of the electricity system. They are central to the 'Green Paper' and the next 'White Paper' that describe the new energy policy of the European Commission (EC); they are also the main driving forces of the R&D energy strategy of the EC.

The relationships between electricity and the E3 areas are very complex and it is not possible to manage the whole system without very efficient and reliable technologies on the one side and without comprehensive and robust management and planning tools on the other side. Research is playing a crucial role, for two main reasons: it provides new technologies that can be used to reconcile the issues of pressure on energy demand and resources, of emission control and of the market conditions in terms of competitiveness. Research also provides the modelling and accounting framework that is needed for a better understanding of the whole electricity-E3 system and for an optimal planning of investments.

As regards the new technologies, there are a number of principles:

- Both supply and demand of electricity have to be considered; from an initially supply oriented R&D activity, we are moving more and more to end-use technologies. A new balance between demand and supply efforts is required in order to ensure the deployment of cost effective demand options and to strengthen the customer and market approaches that are being followed by the utilities.
- Security of supply remains a key concern; for a strategic energy source such as electricity, R&D has to provide diversified systems in order to avoid dependence on one type of system. R&D also has to provide flexible systems to permit rapid transfer from one source to another.
- Similar to the previous points, R&D in support of decentralized systems of production/consumption of electricity has to be strengthened: the changing regimes in the context of market liberalization, the environmental advantages of such systems and the new opportunities they offer for new energy sources, in particular renewable ones, are leading more and more to the deployment of decentralized systems.
- Finally, there is, of course, an optimal allocation to centralized systems and decentralized systems that will be implemented. So, R&D still has to improve the options of the centralized system, in particular those which represent a benefit for the environment, such as clean coal technologies.

Modelling is the second outcome of research; its status is now well established. This is due to two reasons: first, substantial progress was made over the last few years in terms of a relevant representation of the functioning of the energy system, in terms of data and in terms of software; second, the usefulness of modelling in addressing the complex issues of the electricity system is well recognized. Today, policies cannot be presented without quantitative and in-depth analyses of their impacts on the E3 areas.

Modelling has a long tradition; nevertheless, environmental issues and their global dimension have reinforced its interest and its necessity. The Helsinki Conference and the consequent IAEA activities have illustrated this evolution; the DECADES project is a positive outcome of these activities.

The EC has also invested in modelling; the main features of its efforts are as follows:

(a) A large set of energy models has been developed. These models are well known to a large number of the participants of this symposium; they are also well established in the European countries. MEDEE and EFOM, the first generation of tools, followed by MIDAS and HERMES, are well known and I will not go into details. Nevertheless, I will emphasize the fact that such models have been or are part of the decision process for the elaboration of the

EC policies. The application of these models to the assessment of the climate change issue, the preparation of the Green Paper and the design of the R&D energy strategy was crucial and it is important to point out their usefulness.

(b) Large additional efforts have been focused during the last years on the issue of electricity, health and the environment, illustrating the importance of this area. First, a 'green accounting' method for the electricity system has been elaborated. The accounting framework of the environmental costs associated with the full cycle of the different fuels used for electricity production has been quantified both in physical and monetary terms. This activity, performed in co-operation with the United States Department of Energy, the Oak Ridge National Laboratory and Resources for the Future (RFF), which started four years ago, called ExternE, is now well established in Europe and results are being disseminated within the 15 countries of the European Union.

(c) This accounting framework is not sufficient in itself and has to be supplemented by the development of a parallel, new modelling framework; in the jargon of modellers, it is called the 'E3 new generation' and comprises general or partial equilibrium models called SOLFEGE and PRIMES. Strong efforts have been made in this direction because this new generation of models offers many advantages: they integrate fully the environmental dimension in terms of damages and costs, in terms of behaviour and preferences and in terms of technologies; they also represent the new rules of the market and they identify the role of the actors, namely the utilities, the public authorities and the consumers. Such developments are crucial if we want to convince policy makers of the reliability of the figures provided by the models: they must reflect the real situation.

These new modelling tools will be discussed during the symposium; therefore, I will not go into more detail. Nevertheless, I will emphasize the use that will be made of such tools, as this will reflect real motivation.

The mandate of the Berlin meeting includes the definition of objectives and measures for the reduction of greenhouse gas emissions, which calls for intensive and wide application of models. It will be necessary to relate the climate change issue to the new emerging rules of the market; hence, it is crucial to make an in-depth assessment of the electricity issue. The EC is making strong efforts to fulfil this mandate. The study on the "Climate Change Technology Strategy within a Competitive Energy Market", together with other major studies such as "Energy 2020", should help us to define technological options and other optimal actions or instruments, taking into account the complexity of the electricity system. These studies should also help to define the R&D energy strategy of the EC for the next six years.

A logical follow-up to the evaluation of the environmental costs of energy is the question of how to internalize them in the decision making process. More research has to be done to provide answers to the utilities, the public authorities and the consumers of energy. Examination of the role of the different instruments, control and command regulation, taxation, voluntary agreements and their feasibility and acceptance is one of our mandates. It offers the advantage to put into practice and to make operational the vision that we had at the start of the work.

An important point is the willingness of the EC to apply the modelling tools both to the definition of our policies and to the current practice of the actors in the energy sector. This is indeed my first message.

My second message is to point out the necessity of international co-operation in this regard. For global issues, a global answer has to be found, which means that the dialogue must be based on common objectives, concepts and tools.

This Symposium, organized by the IAEA in collaboration with other international organizations, illustrates this necessity. I congratulate the organizers, and I also welcome the participants; their participation means that they are motivated to work with us on the basis of common views.

OPENING STATEMENT

R. Stern
Director,
Industry and Energy Department,
World Bank (IBRD),
Washington, D.C.,
United States of America

The objective of my presentation is to give an overview of the medium and long term options and priorities for meeting the rapidly growing energy demand in developing countries and economies in transition while ensuring environmental sustainability. The investment needs associated with this growth are estimated to be of the order of US $150 000 million per year for the power sector alone and will need to be financed by a mix of national resource mobilization and international capital flows. The main messages I would like to convey to you are as follows: First, I agree fully with the statement of Dr. Blix that energy development is an essential prerequisite for economic development. Second, coal will still account for about one third of the world energy use by the year 2020, despite improvements in energy efficiency and the greater use of renewable energy technologies. Finally, the World Bank feels strongly that financial sustainability through reform of the power sector and sound electricity pricing are prerequisites for environmental sustainability.

How large will the energy demand be and what are the determinants of energy growth?

The total world energy demand will depend on population growth and the per capita energy consumption. The population growth is uncertain, but it is clear that the world is on the verge of a major threshold in comparison with historical rates of growth. The base case projection used by the World Bank shows an increase from the current population of about 6000 million persons to roughly 12 000 million persons by the year 2100, and this is the assumption behind the following projections.

The growth of the per capita consumption will take place in the developing world, but it is assumed that by the year 2030 the per capita energy consumption in the developing world will still be only about one third of that in the developed world. Some might say there is no need for the developing world to follow the energy intensive path followed by the developed world, but even in that case there will still be a major difference between developing and developed countries by the year 2030. The energy use in the OECD countries will remain unchanged, with the additional energy needs in the developed world probably being met solely through efficiency gains. In the developing world there will be a very rapid increase in energy use. Under the above mentioned assumptions, the total primary energy consumption in developing countries is expected to equal that in OECD countries by the year 2000; by the year 2030, the primary energy consumption in developing countries will be 2.5 times greater than that in OECD countries. I want to make clear that this is an energy efficient scenario; if we do not see major gains in energy efficiency, both on the supply side and the demand side, the picture will be different. In fact, our projection is that, by the year 2025, without a price reform, we would have to install in the developing world the equivalent of the entire present OECD capacity. Thus, implementation of a price reform and improvement of supply and demand side efficiency are absolutely essential components of environmental sustainability.

Pollutants

We now discuss briefly some of the environmental pollutants. What are some of the sources of these pollutants and what are the impacts if pollution is not abated? At four main levels, there are:

- Indoor pollution originating primarily from cooking fires and resulting in high levels of respiratory illness;
- Local outdoor pollution in urban areas in the form of particulates, effluents (both solid and liquid from power plants), smog, and lead compounds from gasoline, causing increased illness and environmental degradation;
- At the regional level, acid rain from SO_2 emissions, leading to deforestation and reduced agricultural productivity;
- At the global level, a potential for climate change through the greenhouse effect, which in turn is caused primarily by CO_2 emissions.

It is fashionable in this era to focus attention on global warming, and clearly we will have to do this in the long term, but we must not forget that the most debilitating diseases due to environmental impacts are caused by local pollution. For low income people in developing countries, in both urban and rural areas, indoor pollution is a major health hazard. I was recently in China, and I was again reminded of the danger of local effluents without proper environmental control. It accounts for massive cancer rates as well as very high rates of respiratory diseases; these problems must have high priority generally. Indoor pollution is also a major problem, particularly in the developing world. A typical example in the developing world is the normal cooking arrangement — an open fire inside the house — with massive impacts on the health of individuals. The use of improved stoves leads to significant reduction of indoor pollution.

Regional pollution

To address the problems of growing SO_2 emissions, the World Bank, the Asian Development Bank and the International Institute for Applied Systems Analysis (IIASA) are working together with a network of about one hundred Asian scientists in the RAINS–Asia project to analyse the impact of SO_2 dispersion and sulphur deposition. The RAINS–Asia project models the impacts of growing energy consumption, especially SO_2 emissions and dispersion from sources throughout the region. The impact of sulphur deposition on 31 terrestrial and aquatic ecosystems is estimated according to dose response functions based on previous scientific studies. In some locations, the rate of sulphur deposition already exceeds the local capacity of ecosystems to absorb the acid rain arising from SO_2 emissions. At present, China is most severely affected and will further suffer from the consequences of these emissions because of its high dependence on indigenous coal, even under a scenario of high substitution and high energy efficiency. A recent study, financed by the Global Environment Facility (GEF) on alternative strategies for greenhouse gas abatement, estimated that by the year 2020, even under this scenario, China will still rely on coal for two thirds of its primary energy requirements. If there are no controls on SO_2 emissions, then, according to current projections of the growth in energy consumption, the situation will be critical throughout most of South and East Asia by the year 2020. With modest controls, leading to reductions of SO_2 emissions of about one half of those targeted for Europe and North America, the situation in the year 2020 would be roughly the same as that in the year 1990, although the situation in India would be worse than the present one.

Options for a reduction of pollutant levels

The first option for a reduction of pollution levels is obviously an increase in energy efficiency on both the supply side and the demand side; this would involve very major institutional and policy reforms and investments in efficient technologies. Fuel substitution will also be extremely important, particularly substitution of natural gas for coal and oil, as well as substitution of modern fuels for firewood and dung. Finally, in the longer term, we will have to apply new technologies, such as the use of 'clean' coal and fuel cells, solar power and other renewables, improved fuels for vehicles and emission controls. These measures are not mutually exclusive nor are they substitutes for each other. They are all complementary and, taken together, they can reduce energy related pollution to sustainable levels. I think we have to recognize that this will take time, but it is very important that we move towards developing such technologies, because in the long term they have to provide solutions to our problems. The introduction of pollution reducing practices depends on policy choices among a mix of options, and on technology choices and investments. The appropriate mix of policies and technologies will depend on the situation of each country, its resource endowment and the inevitable trade-offs required to achieve economic development objectives while ensuring environmental sustainability.

How much can energy efficiency achieve?

The World Bank policy for energy development puts emphasis on improvements in energy efficiency, but this does not mean just installing compact fluorescent light bulbs.

In Pakistan, by the year 2000, the energy efficiency programme is expected to save about 2500 MW or about 15% of the projected peak load of 14 500 MW. About one third (32%) would be from supply side measures (power plant efficiency improvements, transmission and distribution loss reduction). About two thirds (68%) would derive from demand side savings, with more than one half of these savings coming from pricing measures, such as time of day pricing for industrial consumers and improved tariff structures for residential and agricultural consumers. The remaining measures are associated with technical improvements, involving investments in more efficient end-use equipment. We should not forget that in the developing world the average energy prices are still only 50% of the long term marginal cost. If we could raise those prices, if we could influence these price increases to lower the demand curve, and if we could introduce peak pricing — something that is still very difficult to do in the developing world, we could achieve half of the gains from these measures, just by shifting the peaks.

Fuel substitution: natural gas

Gas is a very attractive fuel and the environmental benefits and convenience are such that it becomes the fuel of choice where it is available. Natural gas is abundant and has good environmental characteristics, such as low NO_x, low SO_x and low CO_2 relative to coal, and no particulates. The difficulty is that gas is not always available where it is needed; hence gas trade via pipelines or as liquefied natural gas (LNG) is essential. Large, if not huge, investments are required for this, as well as a great deal of international co-operation and a long time period for development. The climate change potential of unburned natural gas is thirty times greater than that of the equivalent amount of coal. As a result, an approximately 5% leakage rate in gas pipelines would negate the benefits from greenhouse gas abatement by substituting gas for coal in a power plant. I was recently in Tokyo, where we are now talking about technical efficiencies of the gas combined cycle of around 60%, something that was quite unimaginable before; furthermore, natural gas has one third of the carbon emissions of coal. But again, as Dr. Blix mentioned, it is extremely important that gas is transported and used efficiently, since otherwise the gains associated with burning gas will be nullified. Nonetheless, gas is an extremely important fuel if we are to address the environmental problems in the medium term.

Fuel substitution and alleviation of poverty

Alleviation of poverty is one of the main objectives on the World Bank's development agenda. One half of the world's population relies on biomass for cooking. Rural populations and poor people in urban areas have no access to low polluting modern fuels and pay a high cost in terms of cash outlays and their own personal labour to procure fuels, and in terms of the degradation of their environment. Biomass is at least five times less efficient than some of the commercial fuels.

What can we do to tackle these problems? A recent study by the World Bank concerning energy strategies for rural and poor people in the developing world reviewed the experience gained from previous approaches to improving access to energy and recommended a significant revision of strategies. First, it is very important to increase the choice for consumers in order to give them the option of spending their limited cash on other fuels. As we have seen earlier, much can be done to increase the energy efficiency of traditional appliances, and much research and application is needed in that area. Reducing the cost of fuel switching is also extremely important. A liquefied petroleum gas cooking ring, even though it may cost only US $25, is beyond the means of many poor people in developing countries. Therefore, special credit schemes and other mechanisms will, in our view, have to be developed so that we will be able to reduce that initial cost of fuel switching. I think, fuel switching is easier in the power sector. We can introduce lifeline tariffs, and we can amortize over a period of time the cost of connecting new consumers, which is also essential, rather than full payment at the time of connection. Finally, we have to level the playing field. It is sometimes forgotten that many barriers to possible alternatives are put up. Very often, there are significant trade barriers, significant tariffs or import quotas, particularly for photovoltaic (PV) systems, which should now become quite competitive in areas that are not connected to the national grid. It is interesting to note the experience in Kenya in the last few years, where the Government did level the playing field and did remove some of the barriers to the import of PV systems, with a consequent explosion in the provision of PV systems in rural areas. A whole industry has formed in Kenya, consisting of small scale suppliers who supply PV systems to the rural population and provide service of these systems. This was made possible by levelling the playing field and by correcting the anomalies in the trade regime.

The clean technology initiatives of the World Bank

The World Bank has launched several initiatives to accelerate the transfer of clean technologies to developing countries. These initiatives call for increased promotion and facilitation of project financing in order to increase trade in gas and commercially viable clean technologies. There are also technologies, such as clean coal technologies and fuel cells, which are in the early stage of commercialization.

Participation of the World Bank could help identify niche applications and opportunities to accelerate the commercialization process.

In other cases, more research, development and demonstration work is required. We are currently exploring, together with the US National Academy of Sciences and others, how an international collaborative effort could be mounted in order to ensure that new technologies will be available in developing countries, where they are needed most to meet the rising demand for energy.

As I mentioned before, the use of PV systems is particularly promising; the cost of these technologies has decreased very rapidly in the last few years, and in many cases, particularly in areas without connection to the grid, they are actually competitive in their own right. Also, the advent of the GEF does give us the chance to buy technologies that are close to being commercial. The World Bank has started a so-called 'solar initiative', the purpose of which is basically to help countries to identify and then develop renewable projects, which can then be financed either in their own right, as fully commercial projects, or by using and leveraging up the GEF. The World Bank has also started the so-called 'clean coal initiative'; the idea of this is to look at the whole fuel chain, all the way through from the mine to the thermal power plant, and to assist countries in applying the newer and cleaner technologies for coal, which is the basis for the energy supply in the major countries connected with the World Bank. By the year 2020, China will still be producing two thirds of its energy from coal, and it is absolutely essential to implement mechanisms to clean up that energy source. This will require the transfer of technologies as well as putting into place institutions and policies that will act as incentives for putting these technologies into place.

Finally, there is a need to promote appropriate research and development, particularly for some technologies; for biomass, for example, very specific technologies will be required that are applied to and developed in and for the third world. The World Bank is trying to put together several collaborative arrangements for this purpose. I would actually be very interested in discussing this with you during the next few days.

Magnitude of the task

The financing requirements for electric power in developing countries will be enormous. For the power sector alone, a capital of approximately one trillion US dollars will be required in the 1990s, or approximately US $150 000 million per year.

Can a policy be environmentally sustainable if it is not financially sustainable?

The answer of the World Bank to this question is "no". The experience in the electric power industry is clear. If utilities are not financially viable, they cannot meet the growth in demand, they cannot build, operate and maintain plants that meet even modest environmental standards, and they cannot attract the private investment needed.

Sector reforms are an essential first step, beginning with correct energy pricing. Commercialization, co-operation and the establishment of a sound regulatory framework are needed to set the stage for increasing private sector participation in debt and equity financing.

If the clients of the World Bank were to increase their average energy prices so that they represent the long term marginal cost rather than keeping them at 50% of the long term marginal cost, they could mobilize US $100 000 million through this increase alone. In fact, most of the financing needs could be met by such an increase. In addition, the private savings, i.e. the global savings from which most of the remainder would have to be funded, are actually there. The average savings rate in the developing world represents approximately 25% of the gross domestic product (GDP). Although they vary significantly from country to country, the savings rates in the countries that have to make the highest investments in East Asia are actually higher than the average of 25% of the GDP. These savings in the developing world amount to 1 trillion US dollars per year, and the energy and power sectors need about 50% of those savings. Thus the resources are available. In order to mobilize these resources, sector reforms will be absolutely essential. Bankrupt State entities will not be able to mobilize private savings. Only entities which are separate from the Government, entities which are subject to competition so that the desperately needed efficiency gains can be achieved and entities which operate in a fairly transparent regulatory environment will be able to mobilize those savings. Indeed, they can become the real sector foundation for the development of the capital markets in many of the client countries of the World Bank. Thus, sector reforms are absolutely essential for financial sustainability and critical for environmental sustainability.

What are the priorities?

Priorities need to be addressed at two levels:

- At the global level, through increased gas trade and acceleration of the use of clean technologies.
- At the country level, through sector reforms in order to enable increased private participation in sector expansion and energy efficient programmes.

Improvement in technical efficiency on the supply and demand sides will only be achievable *and* sustainable within a framework of macroeconomic and energy sector reforms. Appropriate environmental standards are needed, but they must be attainable and enforceable to be effective.

On this basis, energy efficiency programmes can be started. The price reform will lay the basis for successful energy efficiency programmes on the demand side. However, as far as energy efficiency programmes are concerned, I believe that we really need to start thinking afresh about the structure of such programmes for the various countries. Demand side utility models, which are prevalent in the United States of America and in some European countries, are not necessarily those which would be most successful in the developing world. We need to consider new mechanisms through which the new unbundled power systems[1] can encourage energy efficiency on the demand side beyond a mere price reform. We have to find ways to encourage energy service companies so that they can succeed, and we need to develop appropriate environmental standards and try to develop mechanisms to implement those standards, both on the industrial side and with regard to building codes.

A major challenge lies ahead of us, but we are confident that, with a massive reform on the supply side, and with interventions by a combination of the power utility, energy service companies and consumers on the demand side, in parallel with establishing appropriate environmental standards, we have the basis, or we can form the basis, for a world in which long term environmental sustainability for the power sector is possible.

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[1] Restructured power systems, with a number of separate corporations responsible for generation, transmission and/or distribution, or combinations of this, depending on the circumstances.

OPENING STATEMENT

J. Aloisi de Larderel
Industry and Environment Office,
United Nations Environment Programme,
Paris, France

Statement delivered by
G. Mackenzie
UNEP Collaborating Centre on Energy and Environment,
Risø National Laboratory,
Roskilde, Denmark

The United Nations Environment Programme (UNEP) is proud to be a co-organizer of this international Symposium. I am honoured to be able to present this statement on behalf of UNEP. It was in fact to have been delivered by the Director of the UNEP Industry and Environment Office in Paris, Mrs J. Aloisi de Larderel. However, because of the present restrictions on travel by United Nations staff, decided by the Secretary General in view of the budget situation, Mrs Larderel is unfortunately not able to attend the Symposium. As a member of an affiliated centre I am not affected by the ban and therefore I have been given the task of reading the address.

The Executive Director, Ms E. Dowdeswell, and Mrs J. Aloisi de Larderel have asked me to express to you how much they regret not being able to take part. They have asked me to convey to all of you their best wishes for a successful and productive Symposium.

1. BACKGROUND

The need for this Symposium is prompted by two potentially conflicting realities: on the one hand, the world needs more electricity and, on the other hand, we are committed to pursuing a path of sustainable development.

Projections indicate a rapidly growing energy demand in the developing world, particularly in Asia. At the same time there is a growing recognition of the potential negative environmental and social impacts of increasing energy consumption and production. Meeting this growing demand requires investment in power plants and infrastructure, and of course in the appliances and equipment that consume electricity and provide the services we need for human well-being, the industry, transport, etc.

The challenge faced by energy policy makers, public utilities, private power companies and other industries, now and increasingly in the future, is to provide these services in the most *sustainable* way. Determining the most sustainable mix of energy forms and technology requires considering whole systems, matching the quality of energy to the type of energy service, and taking account of economics, the use of natural resources, security of supply, use of labour, public acceptance, as well as the various effects on the environment.

In the four years that have passed since the Helsinki Senior Expert Symposium on Energy and the Environment, there has been a tremendous amount of activity in different centres, exploring and developing new techniques to take account of the environmental and health effects of electricity generation. The aim of this Symposium is to share the experience in approaches, methods and tools for comparing the disparate environmental and health impacts of different technical solutions and options, so that the necessary planning, policy and investments in the power sector are compatible with our objective of a sustainable future.

2. UNEP's ROLE IN ENERGY

UNEP is the United Nations agency charged with responsibility for the environment. The energy programme of UNEP is a relatively modest component of its activities, but it is of central importance.

Why is energy such an important part of UNEP's programme of work? Simply because energy is one factor that plays a role, to a greater or lesser extent, in almost all the environmental issues with which UNEP is concerned: from climate change to the urban environment, from ozone depletion to loss of biodiversity, from pollution of the seas to deforestation and desertification.

Moreover, within the United Nations system, UNEP's energy programme is in a unique position, spanning all forms of energy production and use, in all types of countries, by virtue of the common environmental dimension.

One of UNEP's aims in the field of energy is to reach out beyond the environmental community and to encourage greater incorporation of environmental concerns into the economic decision making process affecting energy production, transportation and consumption. It is in this catalytic role, providing encouragement and information, collaboration and capacity building, that UNEP's particular strength and objectives lie.

UNEP does not have a special policy with regard to *electricity* as such. We recognize nevertheless that electricity is unique among energy forms. Electricity provides the possibility for clean and efficient energy use in households, transport and industry, with enormous potential benefits to human health and well-being. In order to provide electricity to growing populations with increasing standards of living and expanding industries, however, power must be generated in massive amounts. This introduces the risk of potentially serious environmental impacts.

UNEP's primary role in this area is to foster environmental awareness on the part of Member States: to encourage greater incorporation of environmental issues into energy planning and policy.

2.1. New priorities for UNEP's energy programme

During 1995, internal discussions and consultations have been going on within UNEP, to define more precisely UNEP's role in the field of energy. Indeed, all UNEP programmes have been undergoing scrutiny and reformulation. Some of the objectives of the new UNEP energy programme are:

— Establishing UNEP as a key source of information on reducing the environmental impacts of energy utilization;
— Encouraging environmental sustainability in governmental and private-sector decisions on new energy policies, programmes and infrastructure in developing countries;
— Encouraging the increased use of energy efficient technologies and renewable energy technologies through market forces in developing countries;
— Encouraging integrated resource planning in developing countries;
— Defining environmental requirements in contracts for private power producers;
— Identifying and encouraging removal of barriers against implementation of environmentally sound energy options;
— Providing mechanisms to improve the scientific and technical information used by countries to implement the Framework Convention on Climate Change.

The UNEP Collaborating Centre on Energy and Environment, based at the Risø National Laboratory in Denmark, is continuing to expand and will play an important role in UNEP's energy programme. With its international core staff of energy scientists, planners and economists, its network of collaborating institutions and its growing roster of guest researchers, the Centre has supported UNEP in its catalytic role of encouraging the incorporation of environmental aspects into energy policy and planning. This has been done largely through collaborative projects, capacity building and methodological development. This role will be further expanded and is itself an example of the instigating role of UNEP.

3. ENVIRONMENTAL IMPACTS

The generation of electricity can lead to significant environmental effects at different geographical levels and over different time-scales.

3.1. Global issues

The global environmental impacts of energy, particularly power generation, have been at the top of the agenda in recent years. Rapid climate change is perhaps one of the most serious man-made environmental threats ever faced by the world. The latest study from the Intergovernmental Panel on Climate Change (IPCC) indicates that there is a convergence between the predictions of global climate models and the empirical evidence. While nobody can say with certainty whether recent extreme climatic events are due to anthropogenic accumulation of greenhouse gases, the circumstantial evidence is mounting.

Emissions of CO_2 are responsible for about 60% of the global warming impact. Most of this CO_2 comes from the combustion of fossil fuels, and about 30% of this is associated with power generation. With the expanding worldwide demand for electricity and the general expectation that much of this will be satisfied by combustion of coal, it is not surprising that the limitation of CO_2 emssions from the power sector is a central element in a climate change mitigation effort.

UNEP has played a leading role at the international level, as co-founder of the IPCC together with the World Meteorological Organization, and as a partner in the Global Environmental Facility together with the United Nations Development Programme and the World Bank. Of relevance to this Symposium is the work in the field of mitigation analysis.

UNEP has contributed extensively through the support of country studies and the development of a methodological framework for analysing climate change mitigation options. The UNEP Greenhouse Gas Abatement Costing Studies, started in 1991, initially covered ten countries. This activity was instrumental in the development of the methodology and the building of local capacity in participating countries. Studies on a further eight countries will start in the next few months, taking the methodological development and application further. The framework established by the UNEP team and by colleagues in the participating countries has also contributed to the US Country Studies Programme on Climate Change and to the work of the IPCC Working Groups II and III.

3.2. Regional issues

Regional issues, particularly acidification of ecosystems, were in the forefront of our attention during the 1980s. Acidification, caused by long range transport of sulphur and nitrogen compounds, was first considered as a serious problem in Europe and North America in the early 1970s. A number of major projects were initiated in the 1980s, aimed at resolving uncertainties over the causes and effects of acidification. From these projects a broad scientific consensus emerged, and many of the processes that result from pollutant emission, transport, deposition and ecological damage are now well understood.

An attempt has been made to tackle the problem of acidification in Europe through the Convention on Long-range Transboundary Air Pollution of the United Nations Economic Commission for Europe.

Acidification has generally been regarded as a problem confronting the industrialized countries. However, there is a growing danger of acidification problems in *developing countries* where there are ecosystems that are potentially sensitive to acid deposition. Without due control of emissions, severe damage similar to that in some industrialized countries is likely to occur in the future.

3.3. Other environmental impacts

Environmental effects from power production are of course not limited to global and regional air pollution. Power plants also contribute to local air pollution, and there are many other environmental impacts that can be associated directly and indirectly with electricity.

It is important to consider regional and local environmental impacts as well as the global effects. This is not to play down the importance of the threat of climate change. Indeed, addressing the local and regional environmental effects in most cases has a positive effect at the global level. There is a potential for 'win–win' situations; for example, improving consumption efficiency, switching to cleaner fuels and installing modern high efficiency generation equipment with pollution control will reduce pollution at all levels.

3.4. Fuel chains

The consumption of any form of energy involves a chain of processes, each of which can have different environmental impacts. A method for analysing and comparing *fuel chains* was recently developed in a UNEP project by the Stockholm Environment Institute and the UNEP Collaborating Centre on Energy and Environment, and was implemented through case studies in Venezuela and Sri Lanka. *Fuel cycle analysis* goes beyond the typical environmental assessment at the site of energy use or conversion, considering the 'chain' of activities and environmental effects that occur elsewhere as a result of consuming a unit of fuel or energy resource. A more detailed presentation of this project will be given later in the Symposium.

4. ENVIRONMENTAL BENEFITS OF ELECTRIFICATION: THE CASE OF DEVELOPING COUNTRIES

The use of electricity has, of course, beneficial effects, not least for the local environment. The use of electricity in certain industries and in households, instead of fuel consumption, often means higher efficiency as well as less pollution and fewer health hazards.

While the availability of electricity has penetrated virtually 100% in the industrialized countries, there is still a huge potential for electrification in developing countries. An estimated 2000 million people have no access to electricity.

One example of an area where electrification can provide considerable benefits is the household sector, where the use of biomass fuels for cooking leads to serious local and indoor air pollution. It has been estimated that *several hundred million people* (according to the WHO Consultation Study on Indoor Air Pollution and Biomass Fuel, 1991), mainly women and children, are exposed to dangerous levels of pollutants every day, with serious consequences for health.

The provision of biomass fuels often involves environmental damage. It is now generally accepted that the harvesting of wood for fuel is rarely the main cause of deforestation. Clearing of forests for obtaining new agricultural land is the most frequent culprit. Nevertheless, there can be severe local impacts, with large areas of forest being cleared for conversion of wood to charcoal in order to satisfy the demand for cooking fuel for urban households.

Proper ventilation and better stoves offer possibilities for improving indoor conditions, and sustainable forestry can reduce or eliminate the loss of trees. Nevertheless, in many cases, **electrification** would provide a better solution. Electrification of peri-urban areas in developing countries generally requires external assistance, but considerable long term social benefits are expected. The provision of electricity can contribute to a better standard of living, as well as eliminating indoor and local air pollution. Substitution of biomass fuels may also have environmental benefits, although, as noted above, the connection is not always a clear one of reduced deforestation.

5. UNEP's CONTRIBUTION TO A SUSTAINABLE FUTURE

Working towards a sustainable future means fulfilling the needs of society — households, services, industry, transport — in a way which causes least damage to the immediate environment, minimizes greenhouse gas emissions, minimizes the use of non-renewable resources and does not expose local populations to undue risk. All this should be done as economically as possible, thus freeing resources for other essential sectors.

One of UNEP's primary roles is to help Governments and international organizations to take better account of the environment in order to facilitate choices that promote sustainability. This means building experience and institutional capacity, developing methodological frameworks and tools for assessment of the comparative costs and benefits of different options, and demonstrating and encouraging the use of these methods.

The two UNEP activities mentioned, the Fuel Chain Analysis project and the Greenhouse Gas Abatement Costing Studies, are examples of how capacity building and methodological development can be fostered through international collaboration and dissemination of the results to all interested parties, for the good of the local, regional and global environment.

This Symposium provides an excellent opportunity to share our views on the issues and our experience in different methods, to learn from the examples and to discuss how these results and techniques can be applied to help provide electricity to a growing global population in a sustainable way.

OPENING STATEMENT

A. Tcheknavorian-Asenbauer
Industrial Sectors and Environment Division,
United Nations Industrial Development Organization,
Vienna

I am happy to see that major international organizations have come together here to contribute their experience and their views on the crucial issue of energy and the environment. I am particularly gratified to see that an initiative by four Vienna based organizations, namely the IAEA, IIASA, OPEC and UNIDO, started five years ago, has prospered and expanded. It was our aim to establish closer co-operation between organizations having to do directly and indirectly with various aspects of energy. We also believed that the strengths and expertise of each organization can contribute to enhancing the capabilities for incorporating issues of health and the environment in the process of planning and decision making for the electricity sector. The DECADES project exemplifies this approach.

I wish to address here the subject of industrialization, which is inseparably connected with energy. In the next century, 60% of the world's population growth will take place in developing countries and will increase the pressure on already fragile economies. These growing populations need to have access to income earning opportunities, which necessitates the development and expansion of the industrial sector.

We can expect that the industrialization process in developing countries will require a tripling of energy supplies by the year 2025. By that time, 40% of the world's energy consumption will be in developing countries. These countries, like all other countries, are requested to contribute to the common goal of reducing greenhouse gas emissions.

In view of this, the obvious question is how developing countries can secure the growing energy needs for their legitimate development goals and how they can reconcile these with global commitments regarding the environment. In order to find answers to this vital question, we need to identify the critical factors impacting the choice of energy systems.

I wish to recall at this point that the key to sustainable energy development is the need to include socioeconomic, environmental and cultural dimensions in the decision making process. This infers that the analytical tools used in the process must be sensitive to the local conditions to which they are applied. I will elaborate on this.

Typically, developing countries face a number of constraints that influence their energy decisions: inadequate access to appropriate energy saving, clean technologies; a weak infrastructure and engineering capability; lack of investment funds and dwindling foreign aid; shortage of foreign exchange currency and lack of skilled labour. How much these factors constrain the energy policy of a country varies considerably with its general development and its endowment with natural resources. At one end of the spectrum there are rapidly growing economies, such as Brazil, China and India, with vast domestic energy resources and the ability to attract international investment flows to their industrial sector. At the other end of the spectrum there are poor countries, such as Sub-Saharan Africa, with underdeveloped economies, depending largely on traditional energy supplies. This wide spectrum calls for energy policies and for systems that match the realities and priorities of these countries in order to contribute to their sustainable development.

Given these facts, it appears that four major issues play a decisive role in the decision making process of policy makers and energy planners in developing countries:

(1) The potential of energy conservation and energy efficiency;
(2) A sustainable policy for managing the utilization of domestic energy sources;
(3) Flexibility in diversification;
(4) Technological capability.

Let me briefly discuss these issues.

(1) Prior to assessing energy systems, an analysis of the requirements must be carried out, including a viable policy/strategy for reducing the waste of energy. This component is of significant importance in developing countries, regarding both the economic and the environmental dimension. While less energy consumption results in lower emissions and better conservation of natural resources, it also decreases the need for investments in new energy systems; such investments can be prohibitively high for developing countries.

The experience of industrialized countries shows that energy policies favouring energy saving in the industrial sector can bring about significant results. There is ample potential in developing countries for energy saving. Inefficient power generation and excessive use of energy by the industry is a widespread problem. Cost effective improvements in the existing equipment using energy and the application of good housekeeping measures in industries can result in efficiency improvements of up to 40%. The investment requirements for these two categories of energy saving measures are small to moderate. Process improvements, although much more capital intensive, can achieve energy savings of more than 50%.

It follows that decision makers need to examine all available options for energy conservation and energy efficiency, as well as the impact of such measures on the country's economic and environmental goals.

(2) With regard to the issue of a sustainable policy for managing the utilization of domestic energy sources, the following facts have to be considered:

Many developing countries have a shortage of foreign exchange or spend a high portion of foreign currency on imports of energy and fuel. At the same time, many of these countries are endowed with rich domestic energy resources, which can play a significant role in generating employment, with multiplier effects for the whole economy. The existence, extent and quality of domestic energy resources need to be delineated in order to establish their potential for future exploitation. Such an analysis is a vital component of an energy plan. It allows policy makers to establish the method of extraction and the costs of the energy resource, and it enables a comparative assessment of different possible options.

The most abundant energy resources in many developing countries are coal and biomass. In China, for instance, coal provides currently over 75% of the nation's energy supply. The economic dimension of coal as an energy source is obvious.

The environmental impact of coal, when it is used inefficiently, poses serious problems both locally and globally. It is expected that the environmental regulations and the standards for greenhouse gas emissions will tighten worldwide. Developing countries which depend on their coal reserves for meeting their development goals need guidance with regard to a gradual technological change that can improve the cleanliness of conventional coal plants and with regard to new coal burning technologies.

Biomass, particularly wood, traditionally represents an energy resource for rural populations and is important for local industrial structures. In Africa, for example, biomass, mainly wood, provides over 50% of the industrial energy. For some of these industries, such as the rubber, tea and tobacco industries, burning of biomass is an integral part of the production process. Industries processing wood and agricultural products produce wastes, which they use to generate steam for heating and electricity. Many small manufacturing activities, such as rural brick and lime industries, are located near raw material deposits and depend on biomass as their only energy resource.

The use of biomass is, however, often associated with inefficient conversion processes and deforestation through collection of fuel wood. On the other hand, stricter regulations on waste disposal and greenhouse gas emissions are a motive for reconsidering the use of biomass. The availability of efficient conversion technologies and the possibilities to use municipal and agricultural waste as starting material have to be considered pragmatically by energy planners.

(3) Regarding flexibility in diversification, we have to realize that the economic and social conditions in developing countries are very diverse. There are significant differences between urban and rural areas, between large scale industrial activities and small cottage-level industries, and between the levels of transportation systems and the infrastructure in general.

An important socioeconomic goal for many developing countries is the development of rural areas. These areas are often characterized by a low population density and widely dispersed economic activities, which complicates the establishment of energy supply systems. For example, 70% of the rural population in Africa is not connected to a national electricity grid. A further obstacle to electrification is the size of the investments needed for large central power generating facilities. In such situations, decentralized energy systems can be instrumental in generating income-earning opportunities and improving the quality of life of the poor people in rural areas.

New and renewable sources of energy, such as solar power, biomass and small scale hydropower, should be examined in this context. These sources may not be significant enough to be developed for the national or international market, but they can play an important role locally with regard to economic, social and environmental issues.

(4) Finally, regarding technological capability, decision makers must be aware that energy systems are implicitly based on the levels of the infrastructure and the technological capabilities of the originating countries. Industrialized countries have made considerable efforts and provided funds for energy research and development programmes. These programmes are designed to respond to the specific needs of these countries. It is therefore reasonable to assume that international technological co-operation is not necessarily oriented towards the needs of developing countries.

An essential element in the transfer of sustainable technologies is the consideration of the environment into which the technology is being transferred. The effectiveness of technologies depends on their adaptation to the respective environment. Technological changes must therefore go hand in hand with the building of an infrastructure and the enhancement of capabilities and skills. A technology transformation path needs to be defined prior to the introduction of new technologies into developing countries.

In order to assess and compare various energy systems, decision makers need to delineate technology transfer as a strategic component of an energy programme. Thus, the extent to which various technologies can be absorbed and the time and cost needed for that process have to be examined.

In the course of this Symposium we will examine the factors influencing the relationship between energy and human well-being and how these impact energy decisions. My reflections emanate from UNIDO's experience gained from advising developing countries in their energy needs for industrialization. The main lesson we have learned is that, in order to contribute to sustainable socioeconomic development, decisions on energy systems must take into account the specific environmental situation and the needs of the country in which they will be implemented. This fact must be considered in the search for energy systems that can sustain the life and health of future generations.

The challenge for us is to find ways of facilitating this complex task for decision makers. I wish this Symposium every success in this ambitious endeavour.

OPENING STATEMENT

G.O.P. Obasi
Secretary-General,
World Meteorological Organization,
Geneva, Switzerland

Statement delivered by
L.E. Olsson
World Climate Programme Department,
World Meteorological Organization,
Geneva, Switzerland

I am pleased to address this Symposium on behalf of Professor Obasi, the Secretary-General of the World Meteorological Organization (WMO), who is unfortunately unable to participate himself in this important international event, and to convey to you his warmest greetings and his best wishes for the success of the Symposium.

The overall objective of the DECADES project is "to improve the abilities for comparative assessment of different energy chains for electricity generation". The focus is on the characterization of electricity generation technologies, covering the entire energy chains, through the collection of data and information on their technical, economic, health and environmental parameters. A core activity in the project has aimed at the provision of high quality data and user friendly data management and display systems. The project has also reviewed methodologies, techniques and other tools that can be used for such comparative assessments.

Why is this, seemingly fairly technical, project of interest to the WMO? And why would the results of the DECADES project be of interest to the national meteorological and hydrological services (NMHSs)? These services are the focal points for the WMO nationally and it is through the NMHSs that meteorological, hydrological and climatological information and services are provided to socio-economic activities, including the energy sector.

I will try to give an answer to these questions by telling you about some of the programmes and especially about energy related activities of the WMO.

The WMO is a specialized agency within the United Nations system, responsible for the global co-ordination of activities relating to meteorology and operational hydrology.

OBSERVATIONS AND DATA MANAGEMENT

Major activities within the framework of WMO's various programmes are observations, the collection of information and data, managing this mass of information (today, more and more in distributed databases) and, finally, dissemination of information and various products to the public and to specific sectorial users such as the energy sector. The climatological information represents a wide spectrum, from conventional weather observations to special environmental data, and data on ozone and aerosols. These databanks contain oceanographic and hydrological information, data on ozone and aerosols in the atmosphere, as well as information on solar radiation and even data on environmental radioactivity. An increasing amount of remote sensing information, especially from satellites, is also available.

The environmental information represented in the various types of databanks related to the activities of the WMO is thus more or less directly related to the DECADES project.

ENERGY AND CLIMATE CHANGE

There are of course other direct links between electricity, energy and the climate, as an important component of the environment. The energy sector is responsible for more than half of the emissions of anthropogenic greenhouse gases (GHGs). About one-third of all GHG emissions results from energy use in buildings and from disposal of urban waste. Many energy related activities, e.g. production of energy from biomass, hydropower and other renewable sources of energy, are based on extremely climate sensitive resources. Energy may also be considered an important vector that transmits climate sensitivities of socioeconomic systems through the economic system.

'Energy' thus continues to be a priority area in several WMO programmes and activities. The relationships between the many aspects of energy in a societal context and the climate/weather are becoming increasingly evident. Climate and energy are among the prominent driving forces in socioeconomic development. Production and use of energy have a complex impact on the environment, including an impact on climate, and the need for energy is normally directly related to climate and weather.

THE WORLD CLIMATE PROGRAMME

The emphasis on the need for improved climate services for the development of an efficient and environmentally harmonized energy sector is reflected in such documents as the WMO long term plans. The following objectives of the World Climate Programme (WCP) have been formulated:

— To facilitate the effective collection and management of climate data and the monitoring of the global climate system, including the detection and assessment of climate variability and changes;
— To foster the effective application of climate knowledge and information for the benefit of society and the provision of climate services, including the prediction of significant climate variations — both natural events and those resulting from human activities;
— *To assess the impacts of climate variability and changes that could markedly affect economic or social activities and to advise Governments thereon,* and to contribute to the development of a range of socioeconomic response strategies that could be used by Governments and the community;
— To improve the understanding of climate processes for determining the predictability of the climate, including its variability and change, identifying the extent of human influence on the climate and developing the capability for climate prediction.

(In this setting, with the International Atomic Energy Agency as host, it may be appropriate to remember what Einstein once said: "that next to the human brain, the climate system is one of the most complex systems he could think of".)

One of the main components of the WCP is the World Climate Applications and Services Programme. Its objectives include:

— Helping Member States in developing services based on the application of climate information and knowledge for sustainable national development, with emphasis on methods of adaptation to, and mitigation of, adverse impacts of the climate and its variations;
— Promoting awareness of the potential benefits of the applications of climate information and knowledge in human endeavour and the provision of climate services;
— *Providing easy access to practical techniques for applications of climate information and knowledge.*

Another component of the WCP is the World Climate Impacts and Response Strategies Programme, primarily implemented by the United Nations Environment Programme (UNEP) (Dr. Mackenzie from UNEP has already informed us about this). Among its objectives are: "To improve the methodology for climate impact study and response option determinations so as to deepen understanding and improve the simulation of the interactions among climatic, environmental and socioeconomic factors".

The WMO activities in the energy area during the decade 1996–2005 will include:

— Further evaluation of weather and climate implications in energy matters;

— Assessment of the effects of the climate and of climate change on the energy sector;
— Facilitating practical applications of meteorological and hydrological information and related methodologies in various areas of energy conservation, production and distribution.

THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE AND THE FRAMEWORK CONVENTION ON CLIMATE CHANGE

The WMO is pursuing some of the above objectives by supporting the work of the Intergovernmental Panel on Climate Change (IPCC) and the ongoing work for implementing the intentions of the Framework Convention on Climate Change (FCCC). In following up the results of the United Nations Conference on Environment and Development (UNCED), the focus is on Agenda 21. (Many of those who are present here have also actively participated in this work.)

In the FCCC, reference is made to energy, promotion of sustainable development and conservation of resources, as well as the need for adaptation. In particular, it is stated that "the developed country Parties shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties, particularly developing country Parties, to enable them to implement the provisions of the Convention". The Conference of the Parties to the FCCC met for the first time earlier this year and at present the work focuses on the establishment of a mechanism to guide the implementation of the Convention.

The ultimate objective of the FCCC is *"to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner"*.

In a special report prepared by the IPCC in 1994, as an input to the First Conference of the Parties to the FCCC (March 1995), on the basis of a range of model calculations it is concluded that *"stabilization of atmospheric carbon dioxide concentrations ... could be attained only with global anthropogenic emissions that eventually drop to substantially below 1990 levels"*.

As is clearly stated in the IPCC assessments, there are naturally still great uncertainties in the projected consequences of the changes in the composition of the atmosphere. These uncertainties relate to issues such as the feedback from the complex climate system and the regional distribution of potential impacts. One interesting speculation that relates directly to energy production and consumption is the balance between the energy continually received from the sun and human consumption of energy. The climate system is driven by the energy received from the sun, but, within a few hundred years, human consumption of energy may well play a significant role as a driving force in the climate system. Locally, and in some densely populated areas, this impact is already felt, e.g. in large cities, where the urban climate can deviate markedly from 'natural climate conditions' through effects such as the urban heat island.

METEOROLOGICAL AND HYDROLOGICAL INFORMATION FOR ENERGY DEVELOPMENT

The WMO continues to assume the role of the authoritative scientific voice in matters relating to the atmosphere, water and climate in the world arena. One main objective that is in many ways related to issues dealing with energy and environment is to build up the capacities of the NMHSs in the area of energy-meteorology, so that they can serve the energy sector better with relevant information and knowledge.

In particular, the WMO has provided expert advice, capacity building, and both hardware and software to be used in managing information nationally and in regional centres. The CLICOM systems, a PC compatible database/software system for handling and processing climatological data and information, is one core feature in this development. In particular, most of the NMHSs should today have the capacity to provide substantive support in development related to areas such as hydropower, biomass, wind and solar energy applications. A primary requirement is the close collaboration between the producer and the user of the climatological service. In the case of the energy sector, this would normally be between the staff of the NMHSs and the energy engineers.

CLIMATE INFORMATION AND PREDICTION SERVICES (CLIPS)

Scientific and technological achievements in recent years have led, in certain regions of the world, to a drastic improvement in the potential to skilfully predict climate variability on seasonal and inter-annual time-scales. The importance of the so-called ENSO (El Niño — Southern Oscillation) phenomenon was realized particularly through the successfully completed TOGA programme, which was the primary programme in the effort made to describe, understand and predict the onset and evolution of ENSO. The WMO has contributed to this development, particularly through activities within the WCP.

At present, there are several scientific groups engaged in experimental long-lead forecasts of temperature and precipitation anomalies, not only in the tropics but also in selected areas of the extratropics in both hemispheres. The challenge to develop these scientific achievements into user oriented climate application services, disseminated through a network of regional and national centres, will constitute a new focus, especially within the World Climate Application and Services Programme. It is foreseen that this new type of operational climate service will be of special interest to the energy sector, where long-lead forecasts can serve as input to decision making with respect to both energy conservation, demand and production. It is of course essential that the products disseminated are designed to meet the specific needs of the user, thus calling for close collaboration between climatologists and energy experts.

THE CLIMATE AGENDA: INTERNATIONAL CLIMATE RELATED PROGRAMMES

Climate related issues have become increasingly important on the political agenda during the past decades. In particular, national decision making in climate sensitive socioeconomic sectors, such as the energy sector, benefits directly from improved understanding of climate and natural variability and the development of climate related applications. At the intergovernmental meeting on the WCP — The Climate Agenda — in Geneva in April 1993, Governments concluded that, while there had already been substantial achievements, new and evolving requirements would only be met through a greater integration and prioritization of climate related programmes of involved international organizations. The meeting thus called for the preparation of an integrated proposal.

The integrated proposal was presented in spring 1995. In particular, it stresses the need for inter-agency co-ordination of future international climate related activities, which involve four main thrusts:

- New frontiers in climate science and predictions;
- Climate services for sustainable development;
- Studies of climate impact assessments and response strategies to reduce vulnerabilities;
- Dedicated observations of the climate system.

Special attention is given to issues that span all four thrusts, including capacity building and technology transfer.

CONCLUDING REMARKS

The WMO and its Member States, represented primarily by the NMHSs, are engaged in many activities, including special programmes and projects that have direct or indirect relevance to development in the energy sector. In several cases, e.g. hydropower, biomass, solar and wind energy, these activities relate to resource assessment, production and distribution, as well as energy consumption. In some other cases the related activities are more peripheral, although they are necessary and vital for a specific operation.

With increased environmental concern, including the concern about a potential climate change, there is an increased need for environmental impact assessment. In this connection, the services of the WMO and its representatives in the various nations are essential, and major efforts are now aiming at the development of methods for environmental impact assessment. In order to ensure fair judgement of the relative impacts of various energy systems, it is of the utmost importance to make available relevant information. As various strategies for responding to a potential climate change are being considered, the interest in sustainable energy systems and thus the necessity to assess various management options will naturally increase. All this calls for more accurate information and the development of the national capacities to correctly assess alternatives.

From the experience gained, especially through the work of the IPCC, the WMO has come to appreciate the importance of a non-biased attitude in assessing development, be it scientific, technological or socioeconomic. The DECADES project has primarily focused on "comparative environmental impacts of different ways of producing electricity". In particular, the issue of GHG emissions is directly related to questions treated within the mandate of the WMO. Issues associated with human health, as it relates to local air pollution and to comfort, which is influenced by such things as space heating, air conditioning and natural ventilation of urban areas, also have a bearing on the climate, as have the complex risk patterns relating to local climate change.

The WMO appreciates the co-operative framework adopted for the DECADES project and has contributed to the various activities of the project by providing its views and its expertise, to the extent deemed relevant. The work done within the framework of the IPCC has benefitted substantially from the development within the DECADES project. The WMO is thus pleased with the progress made within the DECADES project and is looking forward to a fruitful review of the related activities.

PUBLICATIONS

The WMO has published technical documents, including IPCC reports, covering the field of energy-meteorology, as well as publications covering a wide spectrum of climate related issues.

WMO Publications

WMO No. 550 (TN No. 170)	Meteorological and Hydrological Aspects of Siting and Operation of Nuclear Power Plants; Vol. I (Meteorological Aspects), 1985 (out of print); Vol. II (Hydrological Aspects), 1981 (out of print).
WMO No. 557 (TN No. 172)	Meteorological Aspects of the Utilization of Solar Radiation as an Energy Source (1981) (E, F).
WMO No. 575 (TN No. 175)	Meteorological Aspects of the Utilization of Wind as an Energy Source (1981) (out of print).

WCP Reports

WCP-86	Extrapolation of Mean Wind Statistics with Special Regard to Wind Energy Applications (N.O. Jensen, E.L. Petersen, I. Troen) (1984) (E).
WCAP-13	Information on Meteorological Extremes for the Design and Operation of Energy Systems (G.A. McKay) (1990) (E).
WCAP-14	Extremes and Design Values in Climatology (T. Faragó, W. Katz) (1990) (E).

Technical Report by the Commission for Hydrology

HWR-19	Hydrological Forecasts for Hydroelectric Power Production (1986) (E and R).

OPENING STATEMENT

B.A. Semenov
Deputy Director General,
Head of the Department of Nuclear Energy and Safety,
Chairman of the DECADES Project Steering Committee,
International Atomic Energy Agency,
Vienna

The present Symposium has been organized in the framework of the DECADES project. Therefore, I would like to outline briefly the objectives and scope of the project and to highlight its main achievements and outcomes. The lessons learned from this joint undertaking provide some relevant guidance on the ways and means to develop comparative assessment tools and to assist Member States in implementing comparative assessment in policy making for the power sector. In particular, they illustrate the benefits of international co-operation in this regard. In this connection, my concluding remarks will focus on 'the way forward' and try to identify topics that you might want to discuss later on, in particular during the closing Round Table, in order to outline key issues that could be addressed in the next phase of the DECADES project.

The joint inter-agency project on databases and methodologies for comparative assessment of different energy sources for electricity generation, called DECADES, was established at the end of 1992. Nine international organizations, EC, ESCAP, IAEA, IBRD, IIASA, OECD/NEA, OPEC, UNIDO and WMO, agreed to join their efforts to achieve a common objective, namely: *to enhance the capabilities for comparative assessment of different energy chains in the process of planning and decision making for the electricity sector.*

I should mention that, in addition to these nine organizations who are participating in the DECADES project, UNEP is a co-sponsor of this Symposium.

All these organizations have a mandate and expertise in the field of energy and electricity system analysis and health and/or environmental impact assessment. I would like to stress the importance and effectiveness of the co-operative framework implemented for carrying out the project. This framework has allowed to pull together a broad range of information and know-how, as well as to reflect and integrate viewpoints from experts with different scientific backgrounds. The sharing and exchange of information has enhanced not only the quality of the outcomes but also their credibility and their usefulness for Member States, through helping to ensure that all energy sources — nuclear, fossil and renewable — are treated consistently and objectively.

The overall objective of the project — which I have just stated — takes into account the concerns and priorities of policy makers reflected in the findings and recommendations from a number of international meetings such as the 'Earth Summit' held in Rio de Janeiro in 1992. The findings and recommendations from the Senior Expert Symposium on Electricity and the Environment, held in May 1991 in Helsinki, also provided important guidance on the priority issues to be addressed, aiming towards the objective to enhance comparative assessment capabilities in Member States.

The Steering Committee for the project recognized that there is a very broad range of topics to be addressed, but that not everything could be covered in the project, which was defined for about three years, taking into account the limits on available manpower and financial resources. Therefore, it was decided to focus on high priority tasks that could contribute to building enhanced capacity for implementing comparative assessment in the decision making process. Moreover, it was decided to limit the scope of the project to the electricity sector. Besides the need to focus the efforts on realistically achievable targets, the choice of the electric power sector was motivated by the importance of this sector in terms of sustainable development.

Three major tasks were included in the work programme adopted for the DECADES project, namely:

- Establishment of databases and information systems to support comparative assessment;
- Development of an integrated software package for electricity system analysis and planning (DECPAC);
- Training and support for Member States in implementing comparative assessment.

The work carried out on collecting and making available comprehensive information for supporting comparative assessment of electricity generation options included three main tasks: a survey and compilation of existing information and databases on electricity generation technologies; a systematic collection and consistency checking of data on technical and economic parameters and on health and environmental aspects of different energy chains for electricity generation; and the establishment of a computerized database containing all of the data and information that were collected.

The reference technology database (RTDB), which will be presented during the software demonstration sessions in this Symposium, was developed and implemented over the last two years. Already, it has been distributed to a large number of selected users for testing and evaluation. The RTDB constitutes a large, although not exhaustive, inventory of technologies currently used and under development at different levels of electricity generation chains using fossil fuels, nuclear power and renewable energy sources. Several hundreds of technologies contained in the database are characterized by a detailed set of parameters, covering technical performance, costs, atmospheric emissions, wastes and other environmental burdens.

The users' network provides a mechanism for checking the consistency, and for complementing and updating the information. Feedback from experience is giving guidance on enhancing the capabilities of the computer structure and interface in order to meet better the requirements of analysts and decision makers.

In parallel with the establishment of RTDB, some 15 countries have been given assistance and support in implementing country specific databases (CSDBs), using the RTDB computer system to store information on their electricity chain facilities. Altogether, the databases established by these countries cover more than 1000 technologies. As you will be able to see during the software demonstration sessions, RTDB is running on personal computers and allows the user to access and display numerical, textual and visual information and to print reports on the main characteristics of electricity generation technologies and fuel chains.

Databases alone, however, are not sufficient for carrying out comprehensive comparative assessment of electricity generation strategies. Such studies require analytical tools providing capabilities for energy system analysis and impact assessment.

In the field of methodologies, three main tasks were undertaken within DECADES:

— Preparation of a report describing already available computer tools for comparative assessment of electricity generation options and strategies;
— Development of a new software package for electricity system analysis and planning (DECPAC);
— Preparation of a reference book on integrated electricity system analysis.

The first task was completed by the end of 1994 and a report was prepared on the basis of information provided by software developers from different countries and international organizations. The report is expected to be updated every two or three years in order to reflect the progress and new developments in the field of energy/electricity models.

Within the second task, a new software package (DECPAC) for electricity system analysis was developed, with extra-budgetary financial support from the US Government. This software provides enhanced capabilities for integrating technical, economic, health and environmental aspects into electricity system expansion planning. The software package is linked to the DECADES databases (RTDB and CSDBs) and allows the costs, airborne emissions, solid wastes and other health and environmental burdens of different electricity generation strategies to be analysed. The core features of DECPAC are derived from the IAEA's WASP and ENPEP models for energy/electricity system analysis, which have been thoroughly proven through worldwide use. However, the specific objective of DECPAC is to provide planners with an easy to use tool for carrying out decision support studies for the power sector. Therefore, its design focuses on user friendliness of the graphic interface, enhanced environmental analysis capabilities, extensive reporting capabilities and short running time for optimizing electricity generation system expansion strategies over a period of several decades.

Some twelve teams from different Member States are already testing the application of DECPAC for carrying out case studies and will participate before the end of this year in a workshop to exchange experience and to receive further training. The initial experience with the use of DECPAC has shown that the software is very useful to analysts and planners in the power sector and that it meets a real need.

The IAEA plans to continue maintenance and updating of the databases and software, and to provide training and support in the use of these tools. As I have already mentioned, the first training workshop will be held later this year. Additional workshops are planned — to be organized at national, regional or interregional levels — and groups of users will be established in order to promote exchange of information and know-how between users and to provide feedback to the software developers.

In late 1994, work was started on the third task mentioned above, namely the preparation of a reference book on integrating economic, social, health and environmental issues into policy making for the power sector. Experts participating in various technical meetings of the DECADES project had pointed out that such a book was needed, and the Steering Committee gave its endorsement. The work is led jointly by the IAEA and the World Bank's Industry and Energy Department, with important contributions by other DECADES organizations and national experts; the book is expected to be completed by mid-1996. Issues such as integrated resource planning, external cost valuation and internalization, and multicriteria analysis and decision aiding tools are addressed. It is intended to help policy makers in designing a comparative assessment framework, adapted to their specific requirements and objectives, and in selecting appropriate computer tools for carrying out decision support studies.

Last but not least, in the present DECADES programme of work and achievements, more than twenty country case studies on comparative assessment of alternative strategies and policies for the electric power sector are being carried out. These studies are supported by the IAEA through a co-ordinated research programme. I do not want to elaborate on the results from the studies at this stage, since they will be presented during the Symposium, but I would like to stress that the co-operation between experts from different countries who have different scientific backgrounds has proven to be extremely valuable and effective. In particular, the co-operation and exchange of experience between different teams which are confronted with similar difficulties, such as data collection, resulted in identifying and implementing common approaches for solving the problems. The participation of experts in the fields of electricity system analysis, macroeconomics and environmental impact assessment led to a recognition of the need to reconcile various concerns and priorities — e.g. alleviating local and global environmental impacts and also addressing economic, social and security of supply issues — within a comprehensive assessment of alternatives. The publication of the final reports from the case studies, after their completion by mid-1996, will provide guidance to other countries on the use of comparative assessment in decision support studies.

The results obtained so far within the DECADES project are more than encouraging and demonstrate the effectiveness of joint efforts by international organizations and national experts and institutes. The high interest of experts from Member States — in particular from developing countries and countries in transition — is, from my point of view, the best indicator of the success of the project up to now. This success provides a sound basis for looking ahead to some possible new directions, in the expectation that the participating organizations will support the continuation of the project.

Ongoing activities

Of course, there still remains some work to be done to complete fully the project as it was envisaged by the Steering Committee. Work is continuing on a number of tasks, focusing mainly on the enhancement of the products, their dissemination, and training and support in their use. I would like to highlight some of these.

First of all, there is work to be done to complete some ten reports, including full documentation of the databases, users' manuals for the software, and reports on the case studies that will be completed early in 1996. Also, as I have already mentioned, the reference book on integration of comparative assessment into electricity system planning should be completed by mid-1996.

Secondly, it is planned to organize a series of regional seminars and workshops in order to promote the use of the tools that have been developed, and to give training and support on their use. The first such workshop will be organized later this year, and two workshops are planned for 1996. If the other organizations participating in the DECADES project would be prepared to assist through joint funding, it would be possible to broaden the amount of training that could be given.

Thirdly, it will be necessary to have continuing maintenance, updating and enhancement of the databases and the DECPAC software. Already, based on feedback from users, we see the need to improve the capabilities for modelling intermittent renewable energy systems, for treating cogeneration plants that produce both electricity and heat as outputs, and for modelling multiple-fuel power plants (e.g. using both oil and gas, or coal and oil).

Possible new directions for the DECADES project

The activities that I have just mentioned are tasks that would be aiming towards improving the tools that have been developed in the current phase of the DECADES project. There are also some issues that have been excluded up to now, but that could be addressed in a second phase of the project.

As I have stated at the outset, the Steering Committee decided that the first phase of the DECADES project, which has been largely completed, should focus on the electricity supply sector. However, demand side management is also very important. Thus, it could be useful to define a further programme of work that would add demand side technologies to the databases, and to incorporate analysis of demand side options into the DECPAC model. In this regard, we have maintained close co-ordination with the project on establishing an Environmental Manual for Power Development (EMP), which has been managed by the World Bank. The results from this project could provide a basis for making the suggested enhancements to the DECADES tools.

Up to now, the DECADES project has focused on the calculation of costs, emissions, wastes and other environmental burdens for different energy chains and electricity generation systems. However, this work does not systematically address the health and environmental impacts that may result. The next phase of work could aim towards developing estimates of such impacts, in order to give a more complete comparative assessment of different energy sources. The IAEA has done some work on establishing a database on Health and Environmental Impacts of Energy Systems (HEIES), but more work is required in order to produce a tool that can be used in the comparative assessment process. Also, advantage could be taken of the work that has been carried out by the European Commission, in co-operation with several national research institutes, on the external costs of energy systems.

Finally, I would suggest that a number of studies should be undertaken, using the tools that have been developed, focusing on specific high priority issues, for example the cost effectiveness of different energy systems and technology measures for mitigating emissions of greenhouse gases and other environmental burdens.

Concluding remarks

The work already accomplished in the first phase of the DECADES project, which was started late in 1992, shows that the inter-agency joint project framework is very effective and that the project should — from my point of view — be continued. The present Symposium is a major milestone of the project and provides a good opportunity for reflection and discussion on the use of comparative assessment in support of decision making. I have made some preliminary suggestions on work that could be undertaken in the next phase, but I am sure that the high level experts who are participating in this Symposium will identify other key issues and areas of high priority for further work. As Chairman of the DECADES Project Steering Committee, I hope that the presentations and discussions will lead to some concrete proposals and recommendations that will help the Steering Committee in defining the future work programme of the project, if the participating organizations will support its continuation.

KEY ISSUES
IN THE DECISION MAKING PROCESS

(Session 1)

Chairman

R.K. PACHAURI
India

SUSTAINABLE ELECTRICITY POLICIES
The role of international co-operation

K. LEYDON
Directorate General for Energy (DG XVII),
European Commission,
Brussels, Belgium

Abstract

SUSTAINABLE ELECTRICITY POLICIES: THE ROLE OF INTERNATIONAL CO-OPERATION.

Analysis is an integral part of the policy process. The European Commission has prepared a 'green paper': Options on the Future Orientation of European Energy Policy, and has sent to the Council of Ministers its communication and work programme. Analysis, undertaken in co-operation with the Member States of the European Union (EU), the energy industry (particularly the electricity sector), users, other interested groups and international organizations, was part of this review. The scenario approach has been chosen in the economic analysis, which will be published soon. The principal findings of this analysis are as follows: (a) Energy consumption in the EU is expected to continue to grow moderately, at a rate of somewhat below 1% p.a., through the year 2020. (b) Electricity consumption is expected to grow strongly, increasing its share in the final energy consumption. (c) Fuels with zero carbon content such as nuclear and renewables face certain difficulties regarding extended deployment, for reasons of public acceptance and on economic grounds. Certain renewables (e.g. biomass) are, however, moving towards mainstream acceptance and there appears to be scope for larger scale deployment. (d) There is room for more application of nuclear and renewables in case of a shift in the policy paradigm, i.e. if we move to a 'Forum' type world where globalization, a unity of purpose and restructuring of institutions foster a consensus on effective curbing of carbon.

1. ROLE OF ANALYSIS IN ENERGY POLICY FORMULATION

The European Commission (EC) is the executive body of the European Union (EU). With the recent addition of Austria to the twelve existing Member States, together with Finland and Sweden, the EU now includes fifteen countries. By the end of the decade, other countries, in particular some from eastern Europe, might join the EU, so that it may include more than 20 countries. Energy is an important part of our policy process. The first treaty of the EU was signed in Maastricht in 1992. In 1996, EU ministers will meet in Dublin to draft the text of the next treaty. In preparation for this, the EC Directorate General for Energy has undertaken a review of energy policies. A 'green paper', identifying various options, was prepared and sent to the Council of Ministers several months ago. Now, the time for analysis is over and a choice among different options has to be made. A 'white paper' was prepared, and the Council of Ministers met on 14 December 1995 to discuss this paper.

Part of that policy process is the development of EC methods of analysis. One of the interesting points that has been discussed at meetings between the Council of Ministers and other institutions, as well as between the EC and other interested groups, is the need for an analytical input into the policy process. It is clear that it is not sufficient simply to have the political desire to go in a certain direction, but it is necessary to identify the correct direction in which to go, and this requires a good deal of analysis. A typical example in this regard is the climate change issue, which is a complex mixture of political objectives and scientific and technical inputs, and it is difficult to unravel them. Indeed, some scientists recalled Albert Einstein saying that the climate was somewhat akin to the human mind in complexity. This becomes insignificant in view of the present structure of the world. Climatologists have the easier job, and it is the politicians, the administrators and the actors in the field of energy and economy who have the difficult job of unravelling the social structures behind climate change.

Apart from the link between policy formulation and analysis, one or two technical aspects need to be addressed. There is the need for information on the future of energy, and we have the task of observing and monitoring what is actually going on. Therefore, we have to introduce independent analyses and viewpoints into the discussion, and not just to provide the information that is particularly convenient to a lobbying group or that is of particular interest at a given moment in time. The position of the EC in this matter is that this part of the process has to concentrate on certain key objectives of energy policy, which should focus on three main issues: energy and economy, the problem of trade and competitiveness, and energy and geopolitics. The last point is of particular importance for this Symposium, since the Member States of the EU depend on imports for 50% or more of their energy needs; this will probably rise to the order of 70%. On the one hand, the resources are in our neighbourhood; but, on the other hand, our neighbourhood is undergoing large political and economic changes. The challenges to economists are that the environmental goals have to be met and, at the same time, a rise in the cost of energy as a factor of production has to be avoided. It will not be an easy task to develop new energy services in response to the changing needs, to harness energy efficiency and to develop new technologies and products, and to do all that in an unstable political situation.

2. METHODS OF ANALYSIS

What are the possible methods to handle this situation? The EC has had some experience over the past two years. In September 1993, a paper on the economic foundations for an energy policy was prepared in which the complex role that energy plays in society was identified. Energy is a factor of production, and there is an extraordinarily large geopolitical dimension to the energy trading relationships with our neighbours — Russia and Norway, Algeria and the Persian Gulf area. These are important aspects of our foreign policy relationships, but there are also interconnections with other dimensions, including energy and the environment.

Several years ago, we proposed a carbon energy tax, and we did this with some enthusiasm. This enthusiasm was lacking when we discussed the matter with a number of countries. The appreciation of a carbon energy tax differs from one country to another, depending on the country's energy policy. Consequently, when seeking to achieve an environmental objective, other objectives should not be disregarded. One of the fascinating problems in preparing an analysis is that we have to try to make the very complex interrelationship between different pillars of policy easier to survey. We are entering a transition period of great uncertainty that might last a decade or even two decades. In some ways, it is a historic moment, and we need to be able to deal with massive uncertainties and major political changes. Therefore, we launched the "2020 Strategic Analysis", based on a scenario approach and on our appreciation that the tectonic plates of geopolitics and economic relationships are moving.

Three scenarios were considered, centred on the political challenges and priorities within Europe and the problems facing Governments, since they might influence the energy structures more than internal energy matters. These scenarios were then translated into macroeconomic scenarios and trading scenarios. Also, four possible future marketplace scenarios were identified: Conventional wisdom, Battlefield, Forum and Hypermarket. Their characteristics are as follows:

(1) *Conventional wisdom:* This provides a view of the most likely evolution of events. Economic growth gradually weakens in the long term. Although some progress is made, many of the world's structural, social and economic problems remain.

(2) *Battlefield:* The contradictions and instabilities in the global system make economic integration very difficult. Globalization is seen as too ambitious. The geopolitical system is divided into blocs, with tensions and friction between and within the blocs. This leads to a Europe 'à la carte'.

(3) *Hypermarket:* Global economic integration is self-reinforcing and continues. The force driving this scenario is the continued application of the market mechanism that is regarded as the best way to produce wealth and to handle complexity in uncertain times. Liberalization and privatization lead to new results and encourage new groups of persons with higher demands to enter the market.

(4) *Forum:* The process of global economic integration produces new imperatives for collective public action. National, European and international institutions

are gradually restructured so as to be able to deal more effectively with broader, more complex, shared problems and interests.

Each of these scenarios may present some surprises. For example, in Sweden, Conventional wisdom means that nuclear power will be phased out by the year 2010; however, in France, Conventional wisdom leads to totally different decisions. Therefore, the marketplace scenarios have to reflect a diversity of current thinking.

These scenarios were matched with three technology scenarios: abundant renewables, relaunch of nuclear power (dealing with the problems of how it would take place and what are the conditions to bring it about); and plentiful and moderately priced fossil fuels, which is a new paradigm. Finally, two energy price scenarios were developed: one with a rather high oil price (about US $30 per barrel, as in the IEA scenarios) and the other with a more moderate oil price, which would remain more or less at today's price over the next 20 years or so. Regarding the most difficult issue, the climate change, it was assumed that the precautionary principle mode would be maintained up to the year 2005, but that, around the turn of the century, environmental consequences would become obvious and we would move from the assumption of a possible climate change to the conclusion that such a change will happen and, therefore, that we have to begin to react. These scenarios were applied to the fifteen EU Member States and the focus was on a detailed bottom-up approach. A more complex analysis was done for the neighbouring countries of the EU, namely North Africa, the Middle East, central and eastern Europe and the territories of the former Soviet Union.

Two of the scenarios, Hypermarket and Forum, are very contrasting. Each of them implies a different energy policy, a different taxation policy, a different economic policy and different interest rates. They do, however, highlight the remarkable robustness of the energy sector and its ability to survive and to make money under the conditions of these scenarios.

Concerning the models needed, this kind of scenario analysis cannot be done without a good tool kit. There is definitely a need for new and improved analytical tools. Given the complexity of the policy choices, they cannot be addressed correctly without good tools. Furthermore, these tools have to be used with modesty and with a certain scepticism about the mechanisms of forecasting and analysis. The EC Directorate General for Science, Research and Development has developed several models, for example:

— MIDAS: A model that is central to the present exercise;
— POLES: A long term (2010–2030) world supply and demand simulation model;
— GEM-E3: A macroeconomic general equilibrium model for interactions between the environment and the energy system;
— PRIMES: A partial equilibrium energy system model, covering market structures of the actors in the field of energy and economy.

3. KEY ISSUES EMERGING FOR THE ELECTRICITY SECTOR

Within the area of the EU countries, which is in many ways very distinct from other parts of the world, particularly China and India, the global electricity growth rates considered for the next 25 years are about half of those in the previous 25 years, which is half of what they were 50 years ago. Compared with a historical growth rate of 2.7% p.a. since 1974, the growth rate of the total electricity demand decreases slowly in the period 1992–2020 for the four scenarios:

— Conventional wisdom: 1.34% p.a. (1.0% p.a. after 2010);
— Battlefield: 1.07% p.a. (1.0% p.a. after 2010);
— Forum: 1.26% p.a. (1.3% p.a. after 2010);
— Hypermarket: 1.55% p.a. (1.2% p.a. after 2010).

This means that in each of the different scenarios the annual growth rate of electricity demand is roughly between 1 and 1.5%. This has consequences for the structure of the electricity market.

The analysis of the electricity demand by sector leads to the same findings for all scenarios, namely a reduced growth in the tertiary-domestic sector (0.7–1.2% p.a.) due to improvements in appliances and progressive saturation of electric heating, a sustained growth in industry (1.2–1.7% p.a.) and a bullish growth in the demand for transport (4.5–5.5% p.a.) due to the development of electric cars, resulting in a quadrupling of electricity consumption.

One key task is to identify the main issues of power generation under the four scenarios. Each scenario has different footprints for demand, supply and general economic policy. The Conventional wisdom scenario leads to a slow decrease of nuclear and solid fuel, particularly after the year 2010, with additional requirements being covered by gas. In the Battlefield scenario, nuclear power is stabilized, since this scenario represents the State in its supreme form — the Treaty of Westphalia in European terms, with each country trying to go its own way. Some would say this is a perfect reflection of current thinking within States, between States and between regions, although this may not represent a particularly pleasant world. Paradoxically, it is in a world corresponding to the Forum scenario that nuclear can flourish. This world is also driven by environmental considerations and a spectacular shift away from solid fuels, which are replaced by nuclear and gas. The world according to the Hypermarket scenario is one in which power generation moves away from conventional fossil fuel technologies and from nuclear; massive development of the gas combined cycle is complemented by some new coal technologies. The social discount rate reflects the judgements of the society. The four scenarios have different discount rates, which obviously influences the future energy mix. In Hypermarket the discount rate is 10%, in Forum it is 5%, and in Battlefield and Conventional wisdom it is between these values. Obviously, the investment profile will be different under the market conditions and the trading conditions in each of these scenarios.

TABLE I. CAPACITY ADDITIONS (GW(e)) FROM 1992 TO 2020 IN THE DIFFERENT SCENARIOS

Options	Conventional wisdom	Battlefield	Forum	Hypermarket
Nuclear	42	72	120	37
Solid fuels	80	56	16	36
Combined cycle	156	128	141	220
Other oil and gas	48	49	55	67
CHP[a] and autoproducers	79	65	85	83
Biomass	19	17	39	17
Hydro	21	21	21	21
Other renewables	12	13	28	13
Expansion and replacements	456	419	502	492

[a] CHP: Combined heat and power production.

TABLE II. TOTAL INSTALLED NUCLEAR CAPACITY BY SCENARIO (GW(e))

Year	Conventional wisdom	Battlefield	Forum	Hypermarket
1992	117	117	117	117
2005	122	125	124	122
2020	85	116	164	80

TABLE III. CONTRIBUTION OF NATURAL GAS TO ELECTRICITY PRODUCTION BY THE YEAR 2020

	Year 1992	Conventional wisdom	Battlefield	Forum	Hypermarket
Percentage of total production	6.4	39.7	34.6	30.6	51.4
Gas consumption (Mtoe)	31	218	176	157	290

The power capacity in 1992 was 526 GW(e). The requirements for expansion and replacement up to the year 2020 (Table I) amount to: 456 GW(e), with investments of some 543 $\times$ 10^{12} ECU 93 required for Conventional wisdom; 419 GW(e): 542 $\times$ 10^{12} ECU 93 for Battlefield; 502 GW(e): 660 $\times$ 10^{12} ECU 93 for Forum; and 492 GW(e): 526 $\times$ 10^{12} ECU 93 for Hypermarket. The combined cycle represents between 30 and 45% of the investment in thermal units.

It might be interesting to analyse the nuclear power capacities that would emerge under each of these scenarios (Table II). Conventional wisdom and Hypermarket show a decline in nuclear capacity, mainly in response to economic factors. In the Battlefield scenario the nuclear capacity is maintained more or less constant, mainly by extending the life of existing plants, retrofitting, etc. However, in the Forum scenario there is a significant increase in nuclear capacity. One point to note is that the global climate change issue will probably not be used to promote nuclear energy, but the logic of a nuclear phase-out does seem to be questionable in the face of the need to address this issue. However, this is a controversial point.

4. LESSONS FOR THE FUTURE

Several conclusions can be drawn from the problem analysis of the electricity sector. Combined heat and power is a special issue, and it is very closely linked to European arguments. Concerning the dependence on gas (Table III), it is noted that, at the beginning of the present decade, the share of gas in the power sector was approximately 6%. By the end of the decade and in the first five years of the coming century, gas will have increased its share in the power sector to about 20%. Clearly, there will be some very important issues regarding the security of supply in the gas sector, but I am ignoring that here.

The evolution of the electricity market shows the position of primacy of electricity networks; this is also important to the EC, whose policy is to open up the internal energy market. In other words, the electricity sector is moving from a commodity market to a service market. The EC is observing a trend towards competitive market structures, particularly for electricity and gas. It will be possible to make enormous productivity gains. Thus, changes are taking place on this front, and the analysis confirms the importance of productivity gains in power generation.

Furthermore, the capital market is a global market, and the energy industry has to try to attract resources because our industry is moving away from self-financing and has to turn to capital markets. There is a search for new mechanisms for marketing energy products and for attracting the capital needed by the energy industry. This will have important repercussions on the industry.

Regarding nuclear power, a Forum scenario seems to be required for a relaunch of nuclear power, with high relative prices of competing energy sources. Also, it is necessary to find a solution to the problems of concern to the public and to decision makers, namely siting, waste and proliferation.

According to some people, the risk of a climate change is imminent. The study results for both the Conventional wisdom and the Hypermarket scenarios show that CO_2 emissions will increase by 25% over the next 25 years, corresponding to a growth rate of 1% p.a. For the Battlefield scenario, with a slow economic growth, there is essentially zero growth in CO_2 emissions. It is only in the Forum scenario that we see a significant reduction in CO_2 emissions, by about one third in the power sector. Two indicators, carbon intensity and energy intensity, can be used to show the trends. From 1970 onwards, the energy intensity has improved substantially. The carbon intensity has also changed because of replacement of oil by gas, and by nuclear in the 1980s. Regarding the policy options for the coming years, up to the year 2020, we expect a large improvement in energy intensity.

In conclusion, I would like to point out that we need to link analysis to the policy debate, we need good tools for carrying out this analysis, and we need a decision making framework that reflects the complexity of the choices we now have to face.

MAJOR ISSUES OF ELECTRICITY GENERATION IN DEVELOPING COUNTRIES

H. KHATIB
Honorary Vice Chairman,
World Energy Council,
Amman, Jordan

Abstract

MAJOR ISSUES OF ELECTRICITY GENERATION IN DEVELOPING COUNTRIES.

Rapid growth in electricity generation is taking place in developing countries, where the demand is growing at a rate of 6–7% per year. After the year 2025, the largest amount of electricity worldwide will be produced in developing countries. The growth of the energy demand in these countries will be the main issue on the global electricity scene in the coming two to three decades. The electricity requirements in developing countries will have global effects on energy, fuels and the environment. Electrification and electricity expansion in these countries will have to be financed by their limited developmental and investment budgets. At least 10% of the gross capital formation funds in these countries will be needed for the electricity sector. It is necessary for developing countries to attract local and foreign investment, and the prospects will be enhanced by restructuring and efficient management of the electricity sector. Almost one third of the world's population has no access to electricity. These people, many of whom live in Africa and south Asia, desperately need electricity for improvements in their quality of life. Assisting developing countries in establishing electricity supply systems will not only improve the lot of these people but will also contribute to environmental protection. The efficiency in producing, distributing and utilizing electricity in developing countries is improving, but it is still rather low. Improvement in efficiency is essential for a rational expansion of electricity supply. Improved efficiency in electricity utilization through conservation and other measures will greatly assist in rationalizing the growth in demand and will improve health and environmental prospects. Also of great importance is the choice of proper generation technologies that will help reduce emissions and their detrimental impacts on health and the environment. An investigation of electricity and its relationship with health and the global environment that does not have at its centre of interest the electricity needs of developing countries will miss the main issue.

INTRODUCTION

Before commencing with the discussion and analysis of major issues affecting electricity, health and the environment in developing countries, it is very important to define what a developing country is. Developing countries have a low income, which does not allow them to enjoy the standard of living, the services and the level of welfare that are common in industrialized countries which are members of the

Organisation for Economic Co-operation and Development (OECD). The standard of living in OECD countries is characterized by a high income (average over US $20 000 in 1995), a high life expectancy (78 years), no (or very little) illiteracy and services that are available to the vast majority of the population, particularly accessibility to commercial energy and electricity for almost every citizen.

Even with this broad definition of developing countries, they differ largely, not only from OECD countries but also among themselves. According to the categorization of the World Bank, countries are classified as low income, lower-middle income, upper-middle income and high income countries. In 1993, the low income countries, with a population of more than 3000 million people, had an average income of only US $380 per capita, compared with the high income countries, which had an income of over US $23 000 per capita and a population that was slightly higher than 800 million. Table I gives the population numbers and income classes in 1993 [1].

As can be seen in Table I, more than half of the world population (56%) is in the low income class and the industrialized countries account for only 15% of the world population. If the newly industrialized countries (Korea, Taiwan, Hong Kong, Singapore, Argentina and similar countries) and most of the eastern European countries and the countries of the former Soviet Union are added to the industrialized countries, the total population of these countries does not exceed 1200 million people, i.e. only 20% of the world population; the other 80% of the world population, almost 4300 million prople, live in developing countries. The introduction of the concept of purchasing power parity (ppp), which simply means multiplying the income of these countries by a factor of three, does not change this fact [2].

TABLE I. POPULATION NUMBERS AND INCOME CLASSES IN 1993[a]

Income class	Population (million)	Percentage	GDP per capita (US $)	Number of countries	Category of country
Low	3 100	56	380	59	Developing
Lower-middle	1 100	20	1 500	69	Developing
Upper-middle	500	9	4 300	42	Developing/ newly industrialized
High	830	15	23 000	39	Industrialized
World	5 530		4 400	209	

Source: Ref. [1].

[a] The figures are rounded.

This paper deals with the issue of electricity generation and its relationship with the health and the environment of people in developing countries, regarding their prospects of attaining sustainable development. All of these countries suffer from common problems to varying degrees. Most of these problems are directly or indirectly related to electricity. These problems are discussed in the next sections of the paper, which treat the following issues:

First issue:	Inaccessibility to electricity and to commercial forms of energy;
Second issue:	Capital shortage;
Third issue:	Electricity generation, health and the environment;
Fourth issue:	Need for reforms and restructuring.

This Symposium is being held at a crucial stage in the global development of electric energy. Major changes are taking place in industrialized countries; these changes are prompted by the following factors and developments: (1) The growing environmental concern about the role of energy, particularly electricity production, which causes emissions that have local and sometimes regional or possibly global effects, with long term detrimental consequences. (2) The growing importance of natural gas (also liquefied natural gas (LNG)) as a source of energy, particularly for electricity production; this has enhanced the utilization and development of the gas turbine and its derivative, the high efficiency combined cycle plant, at the expense of the capital intensive traditional steam power stations. (3) The restructuring of the electricity supply industry and the growing importance of competition; this has reinforced the growing trend towards more efficiency and less risk through investing in smaller sets with short lead times. (4) Stringent regulations (environmental and otherwise) and directive conditions, which have increased the cost of new facilities and led to frenzied attempts to rehabilitate, refurbish and repower existing facilities [3].

However, in developing countries such developments will be very slow. Developing countries, particularly those in the low and middle income classes, are mainly concerned with economic development and with making electricity available to an increasing number of people and using it in their activities; utilization of natural resources (e.g. low quality coal) for electricity production is also an important consideration.

FIRST ISSUE: INACCESSIBILITY TO ELECTRICITY AND TO COMMERCIAL FORMS OF ENERGY

Inaccessibility to electricity and to commercial forms of energy is the main challenge for most developing countries in their pursuit of sustainable development. It is also a cause of poor health for hundreds of millions of people, particularly children, and an environmental hazard in almost every low income developing country. Until now, almost 2000 million people in developing countries have no access to a reliable source of electricity and most of these people also have no access to any refined form of commercial energy (other than for minimum lighting). Almost all of these people live in low income countries, and a small number of people live in lower–middle income countries. They depend on fuelwood, animal dung, agricultural crops and garbage, paraffin and coal, if available, as their energy sources for cooking and heating. These activities are carried out in a very inefficient way and therefore the utilization of the heat content of these primitive non-commercial fuels is very low. When an open fire is used for cooking, only 5–10% of the heat content of the fuels is utilized, and the health and environmental hazards are large [4]. In comparison, when gas stoves and ovens are used for cooking and heating, an efficiency of 50% is attained. Because of the high birth rate and the limited area of renewable forests in many developing countries, the amount of fuelwood is gradually dwindling, which is creating even more social and environmental strains.

Most of the people in developing countries live in rural areas. The number of people living in urban areas is increasing rapidly. Until recently, only 15% of the world's population lived in urban areas; according to the United Nations, half of the world's population will live in cities by the year 2000 [5]. Urbanization will, of course, facilitate the supply of services to people in low income countries. This urbanization, however, is taking place through establishment of large informal settlements on the fringes of most urban areas. The proximity of such settlements to urban areas allows people to have limited access to a commercial source of energy, but not to electricity. The availability of electricity is most effective in minimizing health and environmental risks; also, its efficiency is much higher than that of non-commercial fuels [6]. However, few of the low income countries can afford the investments necessary for the development of electricity generation.

Health hazards

The health and environmental hazards of a lack of electricity and of reliance on non-commercial fuels are well known [7]. When non-commercial energy sources are used in homes and at working places, total suspended particulates (TSP), SO_2, NO_2 and CO are commonly emitted. In rural areas of many developing countries, emissions of TSPs and of total volatile organic compounds (TVOCs) of twice the permissible limits have been recorded. It is mainly the absence of electricity and the reliance on low quality and low efficiency non-commercial sources of energy that are causing health risks to people in developing countries, particularly children.

Accessibility to electricity in developing countries

At present, 55% of the world population, particularly people in developing countries (63%), live in rural areas (see Table II). Urbanization facilitates the provision of electricity supply to the urban population; however, most of the people living in rural areas suffer from shortages of electricity supply. There are no statistics giving exact numbers of people in rural areas who have access to a reliable public supply of electricity. Generally, no more than 5% of the rural population in the less developed countries and no more than half of the population in the other developing countries has access to electricity. It is estimated that, as shown in Table II, the number of people worldwide having access to electricity supply of some reliability was around 3300 million in 1992, i.e. only around 63% of the world population. Few of the other people, constituting 37% of the world population, all of whom live in developing countries, have limited access to electricity supply, e.g. through diesel engines for short periods or through batteries.

TABLE II. NUMBERS OF PEOPLE WITH ACCESS TO ELECTRICITY IN 1992

Countries	Population (million)	Rural population		Population with electricity (million)			
		% of total	% with electr.	Urban	Rural	Total	%
OECD, eastern Europe and Commonwealth of Independent States	1210	27	100	883	327	1210	100
Developing countries							
China	1140	66	63	376	479	855	75
India	850	73	10	150	62	212	25
Least developed	440	80	5	44	18	58	13
Sub-Saharan Africa	500	69	5	77	17	94	19
Others	1140	45	63	564	326	890	78
Total developing countries	4070	63	40	1211	902	2109	52
Total world	5280	55	54	2094	1229	3319	63

Source: Ref. [8].

Notes: All populations in industrialized countries are considered to have access to electricity. The figures for China's and India's electrification rates are quoted from published figures and reports to the World Energy Council. It is estimated that only 5% of the rural population and 50% of the urban population in low income developing countries have access to electricity. For other developing countries the figures are 50% and 90%.

Social and productivity impacts of non-availability of electricity

Non-availability of electricity is a handicap for the social, cultural and economic development of nations. Electricity in homes is essential for lighting, cooking and heating, for preservation of food, for access to the media and for entertainment through television. Commercial activities are also severely impeded by the lack of electricity, particularly regarding the use of computation facilities. Electricity shortage affects countries in two ways: it is a handicap in productive activities and it delays social development. Regarding the productivity of a country, electricity shortage discourages possible investors, since it affects production and necessitates higher investments for on-site electricity production or stand-by supplies. For small investors, electricity shortage would increase the cost of operation, since electricity from private generation is more expensive than electricity from public national supplies.

Provision of electricity in developing countries greatly enhances the quality of life. It promotes people's expectations and motivations, thus assisting in elimination of poverty. It also improves health standards and assists in education. Most importantly, it helps retard the migration of people from rural areas to cities and enhances the opportunities for income and employment in those areas. It also assists in preservation of forests and trees, which are currently being cut because of the lack of electricity and energy sources. Electricity is essential for sustainable development; however, so far, little research on the effect of the provision of electricity on social development has been conducted. More work has been done on costing the unreliability of electricity supplies and its economic and social costs. It has been estimated that the losses due to unreliability of electricity supplies may be as high as 4% of the gross domestic product (GDP) in the short term. For India the cost of power shortages to the industrial sector has been estimated at 1.5% of the GDP and for Pakistan at 1.8% [9].

Means of improving accessibility to electricity

Orthodox methods for the provision of electricity supplies, i.e. the erection of a central power station with a transmission and distribution network, which is ideal in industrialized countries and urban areas, may not be the most economic means of providing electricity supplies in developing countries, particularly in rural areas, where the electricity demand per consumer is only a small fraction of a kilowatt. Unorthodox, local or individual techniques have to be investigated in order to reach the target of ensuring electricity supply and to enhance human development.

In rural areas, small diesel sets could be used for many purposes, but these require continuous supply with fuel and spare parts; maintenance of these sets is also required, but people who can do this are not always available. Long interruptions due to broken diesel sets are not uncommon in many countries. It would also be important to exploit mini and micro hydroelectric resources in developing countries if such resources are available. Utilization of photovoltaic (PV) solar cells in households or by small communities is a very important recent development that warrants further attention. Facilities which utilize solar energy need no fuel and practically no maintenance, only a small storage battery. The price of such a facility (10–30 W) for small rural houses, including wiring, is approximately US $600, and the costs are still decreasing. It was claimed that 25% of the rural population without access to electricity could be economically supplied in this way. The same concepts would be applied in rural areas of most low income developing countries in Sub-Saharan Africa and south Asia [10].

Supplying electricity to the 2000 million people who have no access to electricity is a major challenge facing every Government and electrical utility in developing countries. Large funds are being made available by Governments for the development of the electrical system. However, local communities and non-governmental organizations should also take part in this effort. It would be costly and time consuming to wait until the national grid reaches every village and population centre. There is a need for innovative technologies and also for integrated resource planning on a national level to include electricity supplies in development plans in an optimal way [11].

Most cities in developing countries have already an electricity supply of some sort. Therefore, the most important task in these countries is the electrification of rural areas. This poses mainly two types of problems: technical problems and problems connected with the required capital.

On the technical side, the best and most economic strategies for providing electricity supplies in rural areas have to be found. No doubt, the best technical solution would be to connect these areas to the national network (or to the system of a nearby city if there is no national network). This may, however, not be economically feasible or technically possible. Therefore, for each country, the specific circumstances and conditions as well as the existing network configuration have to be studied, utilizing the techniques of the least-cost solution [12]. As mentioned above, innovative techniques also have to be considered. In certain areas, connection to the national network may not be possible because of large distances and technical limitations. Therefore, a promising first step would be to develop local systems, i.e. to promote local electricity generation. The next step may be to connect these local systems to the national grid. However, the problems in connection with generation systems (sometimes based on diesel engines) in rural areas are the difficulties connected with the supply of fuel and spare parts and the availability of skilled manpower needed to run the power stations and to maintain them. Therefore, provisions must be made to solve these problems. One way of facilitating the task is to build hybrid systems with diesel engines that are supplemented by other local resources, such as wind energy or mini hydroelectric resources. Also, central maintenance teams for localized systems could be organized to efficiently utilize local manpower.

In low income developing countries, for example in many countries in central Africa, it may not be economically possible to adopt central or local systems. In these cases, provision of individual small supply facilities based on PV modules, as mentioned above, may be the only practical solution for providing electricity in a very modest way to rural areas. Such modules could be installed in a central village to provide electricity to a clinic, a water pump or a telecommunications system. Alternatively, small PV modules could be used in houses for lighting and for other basic needs. Batteries with a single charging centre could also be used. Such activities could be commercialized in rural areas of developing countries, with participation of private persons and local entrepreneurs. Groups of local entrepreneurs could also start their own local diesel generating systems in villages and sell limited amounts of electricity to the people at a profit, thus filling a gap for some time until the establishment of a national network becomes possible.

One of the means to facilitate rural electrification is to develop economic network configurations, using local materials if possible, for instance concrete or wooden poles, and to produce network materials, particularly accessories. Standardization of rural networks, with local production of some of the materials, would greatly help reduce the cost of rural electrification.

In developing countries, there are other basic needs aside from rural electrification (provision of education, public health, welfare, construction of roads). The role of integrated resource planning is to ensure optimum allocation of the limited capital funds and resources to the different competing uses. The circumstances and means are different in every country; for integrated resource planning on a national level, it is necessary to find the proper level of priority for electrification.

SECOND ISSUE: CAPITAL SHORTAGE

The main reason for inaccessibility to energy and electricity in developing countries is the lack of capital. Electricity systems that consist of generating facilities and a network are capital intensive; a large proportion of foreign currency is required, which is usually not available in many developing countries. The amount of capital needed in the electricity supply industry depends to a large extent on predictions of demand.

Some research has been carried out to predict the future electricity supply requirements in developing countries. During the 1980s, the electricity demand in developing countries has grown at a rate of 8.2% per year; in the 1990s, it is growing at a rate of 6.75% per year, which is 1.5 times the rate of the economic growth. It is expected that in the first two decades of the next century the electricity demand will grow at a rate of 4.5% per year.

Most of the investments in energy systems are used for the electricity sector, but large amounts of money are also required for other energy sectors (refining, mining, distribution of products, building of pipelines, etc.). Generally, 0.6–0.7 of the total investment in the energy sector is used for electricity systems (the exact figure differs from one country to another, depending on its natural resources and the degree of maturity of its energy infrastructure). It is assumed that, by the year 2020, developing countries will produce as much electricity as 12 000 TW·h, which will constitute 45% of the world's electricity production expected for that time. This means that the annual electricity consumption in developing countries will be around 1800 kW·h per capita by the year 2020. In comparison, in 1992, the annual average per capita consumption of electricity worldwide was 2200 kW·h. Thus, after 25 years from now, the electricity consumption in developing countries will still be much below the present average world consumption. In order to reach the above level by the year 2020, electric power stations with a capacity of 3000 GW would have to be built (almost 0.5 kW per capita in developing countries compared with the present 2.5 kW per capita in industrialized countries). The present cost of such facilities is around US $\$3000 \times 10^9$. If a similar investment is allocated to the transmission and distribution system, which is usual for electric power systems, the investment in the electricity subsector will be US $\$6000 \times 10^9$. Comparing this with the total GDP in developing countries of US $\$2700 \times 10^9$ in 1990, which is expected to rise to US $\$4300 \times 10^9$ by the year 2000 and to US $\$9400 \times 10^9$ by the year 2020, gives an idea of the dimensions of the financial burden. If 20% of this GDP is allocated to capital investment, i.e. gross capital formation, developing countries will have to invest US $\$34\,000 \times 10^9$ over the period 1990–2020, with US $\$6000 \times 10^9$, i.e. around 18%, required for energy systems. This demonstrates the very heavy financial burden which the development of the electricity system will impose on developing countries with their limited financial resources. The requirements for investment in the electricity sector are much larger than those for investment in other infrastructural sectors in developing countries [13].

The capabilities of the Governments of most developing countries to mobilize such capital resources are, of course, limited, since in most of these countries priority is given to developmental activities for people, mainly regarding education, health care and employment. However, developing countries need electrical systems for the development of their economy; in order to achieve this, they have to mobilize local capital. Furthermore, they need assistance from other countries, not only by provision of funds in the form of soft and commercial loans but also through investments in the energy and electricity sector by industrialized countries. So far, investments other than those for oil exploration and development have been limited. However, in the past few years, significant amounts of money from international institutions were made available to a few developing countries, especially in the form of direct foreign investments. In order to attract local and foreign capital (and the accompanying technologies), developing countries will have to extend their capital markets and their legal framework, establish regulatory bodies, and create confidence among foreign investors. This is being done in many of the upper-middle income countries, which are on the way to become newly industrialized countries (Malaysia, Turkey and some Latin American countries), as well as in low-middle income countries and in a few large low income countries (China, India, Pakistan, Philippines). These countries are developing their own financial markets, creating a legal and regulatory framework with the guarantees necessary to attract local and foreign investors; thus, they are preparing the ground for attracting private investment in order to compensate for the lack of official assistance and the shortage of governmental funds. However, other, smaller, low-middle income and low income countries (particularly countries in Sub-Saharan Africa and east Asia) have not reached that extent of market sophistication and will continue to depend on official assistance and on governmental funds for many years to come.

Official financial support to developing countries, particularly to the electricity supply industry, is not growing at a pace commensurate with the demand and needs of these countries. Governmental funds also have to be used for other, more important, needs (water supply, sewage system, education, medical services, etc.). Local and foreign investments in the different sectors are required, as well as reforms in the electricity sector.

A major problem in the case of independent power producers is the high cost of financing. Because of the risks involved, private sponsors of projects expect a net return of usually not less than 18-20% on their investment, having paid all operational and other costs, including the costs for loans. This cost of financing is very high, and most of the low income developing countries cannot afford it. These countries often have loans from the International Development Agency (IDA) of the World Bank and from similar development agencies for which the repayment period is long (20–30 years, with a grace period of 5–10 years) and the interest rates are very low (0.75–1% per annum). Developing countries cannot afford the high financing costs associated with new schemes and they also do not have the sophisticated local financial markets and institutions that can help in co-financing and in mitigating some of the risks. The World Bank recently developed financial instruments and institutions that can assist developing countries by providing guarantees and risk mitigation schemes, thus enabling more reasonable financial returns to investors. These institutions include the Multilateral Investment Guarantee Agency (MIGA), the Enhanced Co-financing Operations (ECO) and the International Finance Corporation (IFC).

Independent power production is still taking place in developing countries to a large extent, particularly in China, Colombia, Guatemala, India, Pakistan and the Philippines; in other countries, e.g. Morocco and Turkey, this type of power production is being contemplated and negotiated. Mitigation of risk is essential for developing countries to facilitate larger private investments in electricity systems and to lower the premiums [14].

THIRD ISSUE: ELECTRICITY GENERATION, HEALTH AND THE ENVIRONMENT

Because of environmental and other concerns, most countries in the industrialized world are trying to utilize, whenever possible, environmentally friendly fuels (natural gas and LNG) for their new generating facilities, as well as new technologies with the aim of achieving high efficiency and treatment and control of emissions, sometimes at high investment costs. Developing countries, particularly low income countries, are concerned about cost more than anything else. They try to utilize local fuels whenever possible and available, irrespective of quality; they have to trade efficiency against investment costs and they have to try to utilize local technologies whenever possible, irrespective of other considerations. Also, in most instances, these countries cannot afford large investments for the control of environmental emissions (flue-gas desulphurization, $DeNO_x$ facilities, etc.).

The two largest developing countries, China and India, have large coal resources but small natural gas resources. China has a population of 1175 million and India 900 million, i.e. a total population of 2075 million. This is almost half the population of all developing countries. The potential growth of the electricity supply of these two countries is very high, with a double digit increase in demand in the case of China. Therefore, the performance of these two countries will affect the future of the electricity supply in developing countries more than anything else. Both countries have large coal reserves but small natural gas reserves. China has the third highest coal reserves in the world after the United States of America and the former Soviet Union [15]. The coal reserves of China and India are 11% and 6.7%, respectively, of the global coal reserves, while their reserves of natural gas are only 1.2% and 0.5%, respectively, of the global reserves. Correspondingly, both countries will continue to depend on coal as their major fuel for electricity generation for several decades.

It is not only China and India that will mainly use coal for electricity generation. All developing countries with reasonable reserves and commercially viable resources will continue to use coal as their main fuel for electricity generation, irrespective of other considerations. This applies to Colombia, South Africa, Turkey and, to a lesser extent, Indonesia. Developing countries with large coal resources will not only continue to use coal as their main fuel for electricity generation, but they will also use their own technologies for coal fired facilities. These technologies are usually not state-of-the-art ones and, therefore, emissions can be significant. It will be necessary to promote clean coal technologies in such developing countries, as discussed below.

Electricity production in developing countries is a source of local pollution, particularly in those countries which rely on indigenous coal. Mining and transport of fuel can cause the same degree of pollution as electricity generation. Not only air pollution is caused but also pollution of land and infiltration of pollutants into surface water and groundwater aquifers. Disposal of ash resulting from burning coal can also cause pollution. It should be pointed out that developing countries, particularly those with low incomes, cannot afford the capital investments required for sophisticated flue-gas desulphurization and other $DeNO_x$ facilities. Producing as much electricity as possible at the lowest cost is the main concern of these countries. In many cases this has led to pollution of air and water, with a corresponding impact on the health of people. However, developing countries are becoming increasingly concerned with environmental questions, particularly because of the worldwide efforts made in this respect during the last few years, and they are trying to reduce pollution, particularly from local sources.

Regional pollution is not a major issue in developing countries because of their relatively large areas and the limited use of energy and electricity. So far, only few developing countries are concerned about global pollution, particularly by the emission of greenhouse gases. In some developing countries, global warming due to CO_2 emissions is regarded as being scientifically debatable. Because of resource restrictions and financial limitations, developing countries have great difficulty in securing enough energy resources to enhance their economic development; therefore, it would be very difficult for them to take part in global efforts that would impose limitations on their meagre finances or cause delays of their economic development. The main contribution of developing countries to the global reduction of environmental emissions will be to invest in electricity and energy efficiency and to take energy conservation measures that are economically viable and that do not impose undue strains on their financial resources, which are dedicated to the provision of electricity for the enhancement of economic development. Developing countries should also aim at reducing the existing subsidy structures of their electricity pricing system and they should try to eliminate these subsidies. These countries are, however, not prepared to internalize environmental costs (particularly global ones) into their electricity pricing structures.

The main contribution of developing countries to the protection of the global environment is through adoption of electricity conservation and efficiency measures and the use of clean technologies. A major environmental contribution would be to switch to the utilization of natural gas. This is already taking place in some countries, albeit slowly, for many reasons, the most important one being the lack of capital to invest in national and cross-boundary gas networks. It will be necessary to assist developing countries by technology transfer and provision of capital, so that they can contribute to environmental protection.

The future prospects of nuclear power in developing countries are very limited. Nuclear power reactors are being built only in China, India, the Islamic Republic of Iran and Pakistan. Of the 48 nuclear reactors that are being built, only 14 are in developing countries, eight are in newly industrialized countries, and the rest are in eastern European and in OECD countries [16]. Nuclear power is not expected to play a significant role in developing countries in the foreseeable future. These countries will continue to rely on fossil fuels, mainly coal, and also on hydropower to some extent.

FOURTH ISSUE: NEED FOR REFORMS AND RESTRUCTURING

In most developing countries, the Government plays a dominant role, particularly in the electricity sector. The Government is the owner, the regulator and the operator of power plants. Investments in electricity are very high and only Governments can afford them. The extent of governmental control varies from country to country; however, in all developing countries, the Government has the major role in the electricity sector, not only as a regulator but also as majority owner and manager. Distribution of electricity is sometimes undertaken by private firms, but governmental control of the energy sector is still dominant in most of these countries and the Government also sets the prices. The electricity prices are fixed by the Government, reflecting its social and industrial policies, and in most cases the prices are subsidized. The subsidies vary and their extent depends on the existing local energy resources.

Governments will continue to dominate the electricity sector in most developing countries because of capital shortages, the need for financing and guarantees for loans, and the necessary investments. Governments are, however, not best suited to run utilities and it is advisable to limit governmental control and to encourage the development of markets in order to improve the performance of the electricity sector. Government management and subsidies have led to inefficiency of this sector and to wastage and misallocation of resources. Thus, in most developing countries the electricity sector is not properly managed and is unable to offer services of the required quality and quantity. It is also not able to extend the supply of electricity to those regions where hundreds of millions of people are still not connected to the electricity system. The wastage of resources, the inefficiency and the over-utilization of electricity in many quarters have a direct bearing on emissions and pollution from electricity generation and hence an impact on the environment and the health of people.

All this calls for a change, i.e. restructuring of the electricity sector, to reduce governmental control, thus creating competition on the market and encouraging investors (local and foreign). It is not possible to get rid of governmental control, which has been there for decades, since this might cause political instability. Therefore, the transition from full governmental control to less control has to be gradual and the existing utilities owned and controlled by the Government have to be restructured. The first step may be to establish Government owned but autonomous companies and corporations. Such institutions should be independent and autonomous; they should be accountable for the performance of their plants and they should set the remunerations of their employees and the employment rules similar to those of the private market. Such restructuring is not easy in developing countries, particularly because the existing democratic institutions are often anxious to enhance governmental control in order to protect (in their opinion) public goods and public vested rights (such as subsidies). However, restructuring has been adopted with success in many instances and is one of the best ways of reforming the electricity sector in developing countries. For such reforms to succeed, they must be accompanied by a phase-out of subsidies and by regulatory measures to attract investors (foreign and local).

Development of manpower and managerial capabilities in developing countries is imperative for the development of the electricity sector. The lack of capable managers is a bottleneck; good managers usually work for competitive markets, where their remuneration and promotion depend on their performance, which is usually not possible in the case of electricity institutions dominated and operated by the Government. Restructuring of the electricity sector in a way that would lead to efficient performance under market conditions is desirable in developing countries in order to attract capable managers and to train an efficient labour force. Because of the monopoly of the electricity sector, creation of competition in this sector is not easy, even in industrialized countries. Therefore the successful development of competition in the electricity sector that is taking place in industrialized countries can serve as an example and can provide an incentive for developing countries to follow suit.

It is useful to compare the structure of electric utilities in developing countries with those in industrialized countries. Most utilities in developing countries have a public monopoly, with little accountability, and with control regulations imposed by Governments, which have resulted in poor performance of these utilities. In most industrialized countries there are both private and public utilities (sometimes competing ones), with transparent regulations, as well as information of and interaction with the public. Many developing countries are trying to learn from these experiences, and reorganization of utilities is already taking place. Any attempt at improving the relationship between electricity, the environment and health in developing countries that does not have reforming and restructuring of the electricity supply in these countries as its centre of interest would be missing a vital issue.

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THE POWER SYSTEM IN RUSSIA AND THE ROLE OF NUCLEAR POWER IN THE TRANSITION TO MARKET ECONOMY

L.D. RYABEV
Ministry of Atomic Energy of the Russian Federation

Yu.F. CHERNILIN
Russian Research Centre, Kurchatov Institute

Moscow, Russian Federation

Abstract

THE POWER SYSTEM IN RUSSIA AND THE ROLE OF NUCLEAR POWER IN THE TRANSITION TO MARKET ECONOMY.

As a consequence of the transition of the Russian economic system to market economy, important changes are taking place in the structure of the fuel-energy complex (FEC). Substantial changes have taken place in the structure and the scale of fuel and energy production, for example a decline in the exploitation of oil and coal and a decrease in the production of electric energy by fossil fuelled power plants. Also, the power sector is being restructured. The paper discusses the causes of current problems in the FEC and the role of nuclear energy in the Russian power sector. The results of the Russian-US joint study on the development of the electric power sector and the problems of nuclear power development are also discussed.

1. INTRODUCTION

As a consequence of the transition of the Russian economic system to market economy, important changes are taking place in all parts of the country's economy, including the fuel-energy complex (FEC). Substantial changes in organizations and in the management system of the FEC have already taken place, e.g. formation of joint stock companies and privatization of State companies.

However, major changes in the structure and the scale of fuel and energy production will probably take place because of market reforms in the country's economy. At present, it is possible for Russia to make effective changes to the structure of the FEC, but, because of the further development of market economy, the possibilities of making such changes will decrease. Therefore, a careful analysis of the situation is necessary in order to select the best ways for development of Russia's FEC.

For reliable and safe large scale production of energy, particularly electricity (for which more than one third of the energy resources is used), a number of measures have to be taken. The most important characteristics of such measures are:

— Diversification of energy resources so as to ensure that unforeseen events or failures in one area do not result in the need for abrupt restructuring of the way of life of people;
— Assured supply of energy resources and technologies that have been proven, so that there is no danger of an excessive rise in the cost of energy;
— Acceptable levels of safety and of the impact on humans and the environment.

These characteristics (or the requirements for them) determine the need to use different energy resources (coal, oil, gas and nuclear energy), ensuring that each of them contributes a comparable share of the total energy production.

Energy utilization in Europe (and in the whole world) has increased to such a level that it is not possible for a country to develop its energy system in isolation. The impact on the environment (acid rain, pollution of air and water, etc.), the supply of fuel and other problems of energy and electricity production are transboundary issues, and general agreement on an energy policy is the only reasonable way of resolving them.

2. THE ENERGY COMPLEX OF RUSSIA

2.1. General situation

Before 1988, the exploitation of energy resources in Russia had increased continuously, up to 13% of the worldwide exploitation, while the population of Russia was less than 3% of the world population. At the beginning of the 1990s, as a result of the breakdown of the Soviet Union and the general economic crisis in Russia, the exploitation of energy resources and energy generation began to decline. Compared with the maximum levels achieved, in 1994 the exploitation of fossil fuel resources had declined to 60% for oil, 61% for coal and 95% for gas; electricity production had declined to 86%.

In 1994, the total production of primary resources was 77% of that in 1990, and energy consumption was 86%, while the gross domestic product (GDP) decreased to 60%. At present, the lower rate of decline in the demand for fuel and energy compared to the production dynamics is due to the stability of and even a slight increase in the energy consumption in the public services and the agricultural sectors, as well as an increase in the specific energy consumption (i.e. energy consumed per unit of output) in the industrial sector. The latter is a result of the underutilization of capacities and the relatively slower decrease in production of the energy intensive sectors of the industry. As a consequence, there was a more than 1.4-fold increase in the already high energy intensity of the GDP in 1993 compared with that in 1990. Unfortunately, we have to expect a further decline in the exploitation of fossil fuels. On the contrary, the uranium resources, mainly the stocks of already extracted cheap uranium, would be sufficient for the development of nuclear power until the year 2010. It should be pointed out that, in recent years, nuclear power plants (NPPs) have operated more reliably than fossil fuelled power plants.

The technical level of the operating facilities in all branches of the FEC has become critical. The design lifetime has expired for more than half of the facilities in the coal industry and for 30% of the gas pumping stations. The depreciation of almost half of the oil extraction facilities is more than 50%; more than one third of the gas supply facilities and more than 20% of all thermal power plants will have to retire by the year 2000. According to the present safety standards, it will be necessary to reconstruct about half of the operating NPPs. Because of these facts and many other factors, there is a real danger to long term energy supply in Russia. Some of the reasons for the FEC crisis in Russia are the following:

— The policy of increasing oil and gas extraction at all costs in order to compensate for the deteriorating economic efficiency, and the deceleration in scientific and technical progress.
— The very low level of efficiency in the use of fuel and energy, mainly in the FEC. It is obvious that large losses during extraction, transportation, storage and reprocessing of fuel have a negative impact on the environment.
— The artificial support of low prices for fuel and energy resources and, accordingly, the unprofitableness of the fuel extraction industries.
— The desire to continuously increase the export of crude oil and gas. For a long time, part of the exported oil and gas was at unreasonably low prices, for political reasons.

The Chernobyl accident, which was followed by a compulsory change in the development strategy of the power sector, mainly in respect of the structure of fuel supply, had a serious effect on the operation of the country's FEC. Before 1986, accelerated development of nuclear power was assumed in the official energy programme; nuclear power was supposed to cover all necessary capacity additions in the European part of Russia. In accordance with these plans the rate of NPP construction was very high. It was assumed that the total installed capacity of NPPs would amount to 55 GW(e) by the year 1990, 85 GW(e) by the year 1995 and about 130 GW(e) by the year 2000. However, after the Chernobyl accident, construction of new NPPs was almost cancelled and most of the necessary capacity additions were provided by gas fired plants. For an analysis of the FEC it should also be noted that, since the beginning of the 1980s, there was some lag in the development of the coal industry, which resulted, in particular, in a decline of the exploitation volumes and of the coal quality. In addition, the construction of new coal fired power plants was practically stopped. This means that the majority of operating coal fired power plants do not meet the current environmental standards and will have to be reconstructed; these standards have beome more stringent over the last twenty years, but the necessary measures for improving the environmental features of operating coal fired power plants have not been implemented.

An analysis of the ecological situation in Russia shows that the discharges from fossil fuel power plants account for a considerable part (more than 25%) of all harmful discharges from industrial installations. About 60% of the discharges come from thermal power plants in the European part of Russia and in the Ural, where the ecological burden is substantially above the set limits. At present, the ecological situation is worst in the Ural, in the central region and in the Volga region, where the burdens due to sulphur and nitrogen fallout are 2 to 2.5 times the critical values.

The scale of atmospheric contamination by discharges from thermal plants is characteristic of the technical level of the plants and of their pollution abatement systems. Published data indicate that at present the discharges of ash, sulphur dioxide and nitrogen oxides from operational thermal plants are several times higher than those specified in standards that were established in 1989.

2.2. Electric power

The power sector of Russia is structured as an integrated power system (IPS). The Russian IPS (including the eastern part) accounts for 96% of the electric power generation and for approximately 94% of the installed capacity of electric power plants in Russia. The generation capacity and the percentage shares of different types of power plant in the Russian IPS at the end of 1993 are given in Table I, which shows that approximately 70% of the total power generation capacity is concentrated in the European part of Russia; all NPPs are located in the European part of Russia; most of the existing capacity (68%) is concentrated in fossil fuelled thermal power plants; the thermal capacity is represented by combined heat and power plants (CHPs), which account for 36% of the total capacity, and condensation power plants (CPPs), which account for 32% of the total capacity. Figure 1 shows the shares of the different fuels used in Russian CPPs in the period 1980–1992. The portion of hydropower plants varies widely in the different regions; in the European part of Russia they account for only 13% of the total power plants and in the eastern part they account for 38%.

Eight nuclear power stations, operating in the central, north-west, middle Volga and Ural unified electric power systems, represent the backbone of the Russian nuclear power. These stations have 25 nuclear power units with a total gross capacity of about 21 GW(e).

Four major reactor types are in operation: the RBMK-1000 (11 units), the WWER-1000 (7 units), the WWER-440 (6 units) and the BN-600 (1 unit). These units can be divided into two groups in terms of safety level: (1) the units with first generation WWER-440 reactors and the RBMK-1000 reactors (13 GW(e)); and

TABLE I. GENERATION CAPACITY AND PERCENTAGE SHARES OF DIFFERENT TYPES OF POWER PLANT IN THE RUSSIAN IPS AT THE END OF 1993

Type of plant	IPS of Russia		European part (including the Urals)		Eastern part (including Tyumen)	
	GW(e)	%	GW(e)	%	GW(e)	%
Hydro	41.7	21	18.1	13	23.6	38
Nuclear	21.2	11	21.2	16	—	—
Thermal	135.8	68	98.1	71	37.7	62
CHPs	72.7	36	53.9	39	18.8	31
CCPs	63.1	32	44.2	32	18.9	31
Total	198.7	100	137.4	100	61.3	100

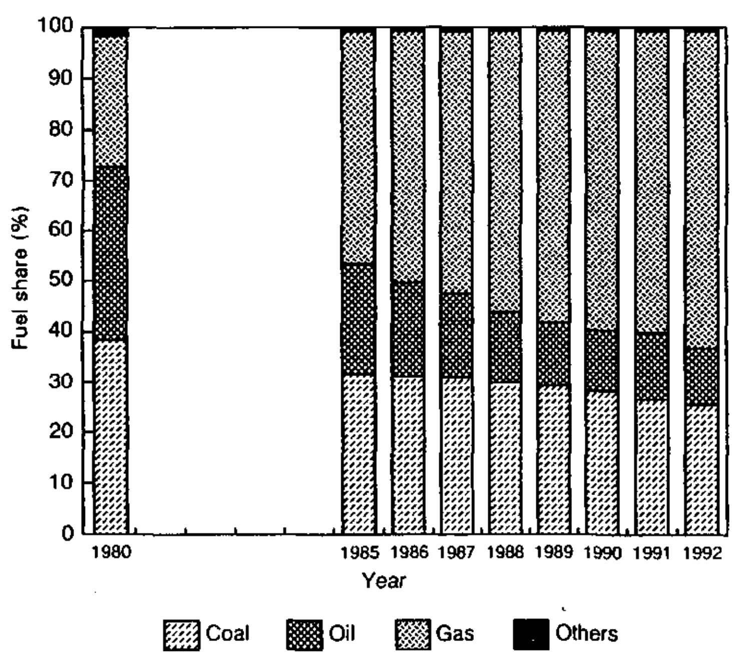

FIG. 1. Shares of fuels used in Russian CPPs in the period 1980–1992.

(2) the units with second generation WWER-440 and WWER-1000 reactors and with the BN-600 reactor (8 GW(e)). The reactors in the first group will require safety upgrading (modernization) to improve their safety and to permit their operation until the end of the design service life.

An important consideration for the future of the nuclear power sector is the advanced state of construction of a number of incomplete units. The Rostov-1 unit is 95% complete, Kalinin-3 is 70% complete and Kursk-5 is 80% complete. Construction has started on Balakovo-5 and -6. The completion of construction of these units might be a good opportunity for restarting nuclear power development in Russia.

TABLE II. FUEL AND ENERGY PRODUCTION IN RUSSIA'S FEC, 1985–1994

Fuel	Units[a]	1985	1988	1990	1991	1992	1993	1994
Oil	mill t mill tce	542 774	568 811	518 740	461 658	461 658	355 507	340 458
Gas	10^{12} m^3 mill tce	462 531	590 679	640 736	643 740	640 736	618 710	607 698
Coal	mill t mill tce	395 257	425 276	396 257	345 224	328 213	306 196	261 167
Electricity production (hydro)	10^{12} kW·h mill tce	160 51.7	161 52	167 54	168 54.3	172 55.6	176.4 57	179 58
Electricity production (nuclear)	10^{12} kW·h mill tce	99.3 33.3	126 42.2	118.3 39.6	120 40.2	119 40.1	118 38	104 32
Total	mill tce	1647	1861	1827	1716	1703	1508	1413

[a] mill t = million tonnes, mill tce = million tonnes of coal equivalent.

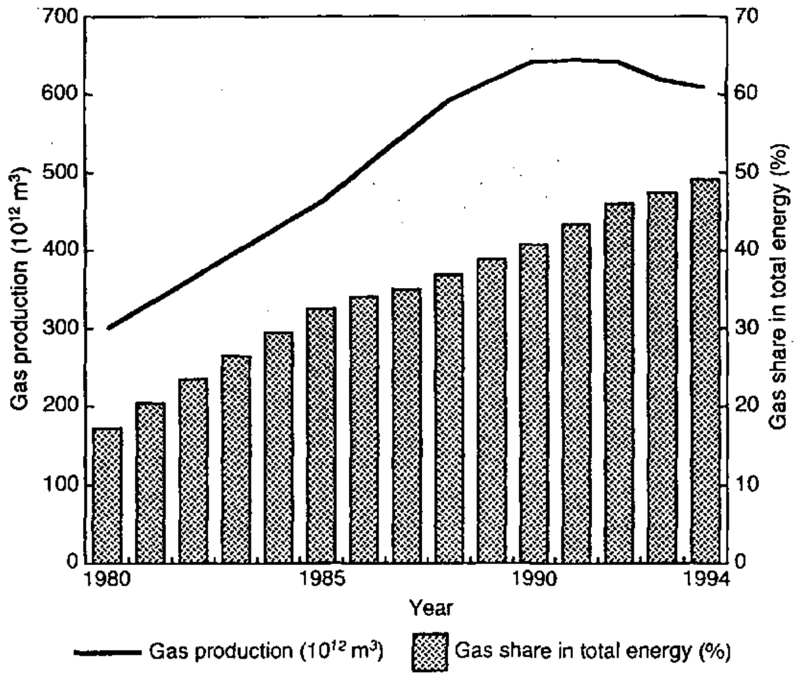

FIG. 2. Production of natural gas and its share in the total energy balance of Russia.

2.3. Fuel resources

The most substantial changes in Russia's FEC have taken place in production and consumption of fossil fuels. These changes relate both to the scale of fuel production and to the consumption structure. Data for fuel and energy production in the period 1985–1994 are presented in Table II. It can be seen that the production of oil and coal has substantially decreased, whereas the production of natural gas has substantially increased.

From 1985 to 1990, production and consumption of natural gas in the former Soviet Union have increased extremely rapidly, with Russia being the main producer of gas (more than 80%). Today, Russia is the largest producer of natural gas in the world (~640 × 10^{12} m^3 in 1992) and also the largest exporter of natural gas in the world (~200 × 10^{12} m^3 per year). The main consumers of Russian natural gas, apart from the countries of the former Soviet Union, are the countries of western Europe.

The rapid growth rate of production and consumption was due to the low production cost and the low levels of investment required, particularly in the initial phase of large scale utilization. Within an astonishingly short time, natural gas assumed a leading position in the country's fuel–energy balance (see Table II). As can be seen from the data presented in Fig. 2, in 1994, gas accounted for nearly 50% of the country's fuel–energy balance. An analysis of the basic data, presented in Ref. [1], suggests that the share of natural gas in Russia's fuel–energy balance will continue to increase by an average of about 1.5% per year; by the end of 1997, the consumption of natural gas could reach some 55% of the country's total fuel consumption. The share of gas in Russia's electric power industry was more than 52% in 1993, with a total consumption of gas in the power sector of more than 200×10^{12} m^3 per year, which is the highest in the world. One argument that is frequently used to justify the Russian 'gas policy' is the assumed existence of large reserves of natural gas (Yamal, Barents Sea, and so on). It is for this reason that the shift to a power industry based on a single energy resource (which has already taken place) is considered by some to be quite acceptable and justified. However, this policy is very difficult to understand from a logical, scientific point of view if a number of factors are taken into consideration, including the fact that the main part of the natural gas in Russia (~92%) is extracted from fields in the Nadym–Pur–Taz group (Tyumen region), which are near their production peak, and the need to open up new fields, which requires very major investments [1]. To illustrate the last point, gas production dropped from 640×10^{12} m^3 to about 606×10^{12} m^3 from 1992 to 1994 (see Fig. 2). According to Ref. [2], the extraction of natural gas will decline further.

In summary, it should be noted that the trend towards further expansion of the 'gasification of Russia' is dangerous, for the following reasons:

— There are no precise estimates of natural gas reserves in Russia, both in terms of volume and of the potential cost of extraction, which will undoubtedly increase. Earlier investigations (e.g. Ref. [3]) stress that "any predicted increase in gas reserves is not very reliable".

— The risk associated with large scale utilization of natural gas is extremely high and it is difficult to predict the environmental impacts of large scale gas extraction and transportation.

— The gas fields in Russia are very far away from the places where the gas is utilized on a large scale and so there is a need to build gas storage facilities with a volume sufficient for the level of consumption.

— The role of natural gas in Russia's economy may turn out to be similar to that of oil, whose 'cheapness and accessibility' are well known.

All of these factors pose a serious threat to the strategic safety of Russia's power industry.

3. PROSPECTS FOR THE DEVELOPMENT OF THE ELECTRIC POWER INDUSTRY IN RUSSIA: THE ROLE OF NUCLEAR POWER

The aforementioned shortcomings in Russia's energy policy, which is oriented towards intensive utilization of natural gas, may be offset to a considerable degree if gas is regarded as just one of a number of equally important energy resources necessary to ensure an acceptable degree of diversity; the share of natural gas in power production should not exceed 25–30%. For such a scenario, nuclear power is the only energy resource that can help ensure a future energy structure that is sufficiently reliable and balanced in terms of independent energy resources. Coal cannot be used to solve the problems in the foreseeable future, mainly for economic reasons, i.e. because of the very large capital investments required for bringing the mining technology up to date and for protection of the environment, and also because of the high transportation cost. Furthermore, apart from the high cost of transportation, any increase in the supply of coal to the European part of Russia is restricted by the capacity of the main transportation artery — the Trans-Siberian railway.

Nuclear energy, as a necessary component of power production in Europe and in Russia, has the following advantages:

- The scale of development of nuclear energy is not restricted by existing stocks of energy resources (fuel).
- Nuclear energy helps reduce the environmental impact that is associated with the exploitation, transport and burning of fossil fuels.
- Nuclear energy is not nearly so sensitive to changes in domestic economic mechanisms and to political miscalculation as is energy production by the use of fossil fuels; this has been confirmed by an analysis of the exploration of all alternative energy resources, including nuclear energy, under current conditions.
- Nuclear energy helps keep down the cost of energy resources and the cost of energy production.

If nuclear power in Europe and Russia develops as expected, the fuel resources of the regions where natural gas is extracted are such that, for a considerable period of time, these regions will be self-sufficient (natural economy) and not dependent to any significant degree on other regions. By developing its domestic nuclear power industry, Russia would be able to provide hydrocarbon raw materials over a long period, not only for itself but also for other European countries, both for technological use and for power production in densely populated European countries for which it is difficult to develop nuclear power on the required scale. In future, it might also be possible to transfer electricity from NPPs in Russia to European countries. The electricity produced in NPPs could also be used for pumping natural gas through pipelines, thereby saving at least 10–15% of the gas produced (see Table III).

TABLE III. NATURAL GAS PRODUCTION, CONSUMPTION AND EXPORT BY RUSSIA IN 1992

	10^{12} m^3/a
Production of natural gas	640
Part consumed in pipelines	60
Total comsumption of natural gas	385
Part consumed by the power industry	about 205
Export of natural gas	about 200

Increased utilization of nuclear energy involves the use of advanced technology, for which a high level of know-how, a safety culture and an increasing number of qualified people are needed. Not only will it help provide more peaceful solutions to economic and political problems in the future, but it will also lead to a reduction in the material and energy requirements of the population. At the same time, it will help resolve the emerging problem of having to take into account not only the interests of the present generation but also those of future generations. Harmonious and long term development of Russia's fuel and energy programme, making allowance for the required level of export of hydrocarbon raw materials and energy to European countries, will only be possible if nuclear power is developed further in Russia.

Nuclear power production may be cheaper in Russia than in Europe, for the following reasons:

- A large number of NPP sites exist which are acceptable from economic, environmental and safety points of view;
- There are ample cheap construction resources;
- There are qualified professional staff and training institutes;
- A trained workforce is less costly;
- Russia has the necessary infrastructure and the full range of enterprises capable of producing large scale equipment for NPPs;
- Russia has an assured supply of nuclear fuel for several decades to come and it has high capacity enrichment facilities;
- Russia has already made significant progress in the field of fast reactor construction and in the closing of the fuel cycle.

TABLE IV. ESTIMATED COSTS FOR UPGRADING OF RUSSIAN NPPs
(million US dollars in 1994 currency values; Russian conditions)

		RBMK-1000	WWER-440	WWER-1000
Direct cost	Max. Min.	89.0 34.7	39.0 9.8	28.1 15.2
Indirect cost	Max. Min.	19.8 7.7	13.6 7.1	15.2 9.9
Basic construction cost	Max. Min.	108.8 42.4	52.6 16.9	43.3 25.1
Unit contingency	Max. Min.	16.9 6.6	8.2 2.6	4.4 2.6
Total cost	Max. Min.	125.7 49.0	60.8 19.5	47.7 27.7
Duration		24 months	21 months	18 months

The necessary preconditions for a serious approach to the development of nuclear energy in Russia have been fulfilled. However, it will be necessary to establish and implement an economic mechanism that ensures this development and attracts capital to this branch of the industry. This will be difficult to achieve solely on the basis of economic interest, and it will be necessary to take political decisions, particularly with regard to the utilization of the vast stocks of mined uranium in Russia that can serve as a collateral for the required capital.

If such a mechanism could be developed and if the required capital could be attracted, it would be possible to solve the problems facing nuclear power in a cost effective way, as has been demonstrated within the framework of a joint Russian–US investigation into alternatives for the development of the electric power industry [4, 5]. Section 4 gives the details of this study. A report on the part of the study devoted to nuclear power presents general and detailed results [5]. The work included cost estimates (see Tables IV–VII) for such measures as the modernization of Russia's NPPs to enhance safety, completion of the construction of NPPs and decommissioning of NPPs.

TABLE V. ESTIMATED COSTS FOR COMPLETION, CONVERSION AND CONSTRUCTION OF RUSSIAN NPPs
(million US dollars in 1994 currency values; Russian conditions)

		Completion Kalinin-3	Conversion Rostov-1	Construction WWER-640 (NP-500)
Direct cost	Max.	102.0	488.1	430.1
	Min.	—	—	344.1
Indirect cost	Max.	98.7	95.6	129.2
	Min.	—	—	103.3
Basic construction cost	Max.	200.7	583.7	559.2
	Min.	—	—	447.4
Unit contingency	Max.	42.2	208.4	232.7
	Min.	—	—	186.1
Total cost	Max.	242.9	792.1	791.9
	Min.	—	—	633.5
Duration		26 months	24 months	72 months

For further development of nuclear power in Russia it is necessary to carry out the following tasks, which undoubtedly have economic effectiveness:

— Implementation of measures to enhance the level of safety and reliability of operating NPPs; completion of previously started NPP construction;
— Resolution of problems regarding radioactive waste management, including those related to spent nuclear fuel;
— Development of up-to-date complex mathematical models for evaluation of the economic and strategic role of nuclear power in the economy of all countries.

In addition, there are tasks which, although they are intended for the future, should already be started and whose cost effectiveness still cannot be fully estimated, i.e. closing of the fuel cycle for transuranic nuclides, transmutation of long lived fission products and use of thorium in NPPs.

TABLE VI. ESTIMATED COSTS FOR DECOMMISSIONING OF RUSSIAN NPPs (million US dollars in 1994 currency values; Russian conditions)

		RBMK-1000	WWER-440
Direct cost	Max. Min.	28.2 —	15.5 —
Indirect cost	Max. Min.	153.5 147.3	98.2 93.7
Basic cost	Max. Min.	181.7 147.3	113.7 93.7
Unit contingency	Max. Min.	27.3 22.1	17.0 14.1
Total cost	Max. Min.	209.0 169.4	130.7 107.8
Duration		43 years	43 years

TABLE VII. COMPARISON OF THE COST ESTIMATES FOR RUSSIAN AND US CONDITIONS (million US dollars in 1994 currency values)

	Russian conditions	US conditions	Ratio
Upgrading of WWER-440	60.8	87.5	1.44
Completion of Kalinin-3	242.1	560.9	2.32
Construction of NPPs	792.1	1454.6	1.84
Decommissioning of WWER-440	130.7	640.4	4.90

It should be pointed out that, after the completion of work to enhance the safety of NPPs following the accidents at Three-Mile-Island-2 and at Chernobyl, the worst possible consequence of these accidents for us and for future generations would be a political decision to stop the utilization of nuclear energy. The potential, the technological capability and the feasibility of the realization of promises are much greater for nuclear power than for other energy technologies.

4. JOINT ELECTRIC POWER ALTERNATIVES STUDY (JEPAS)

4.1. Purpose and contents of the study

Following an agreement between the American Vice President Gore and the Russian Prime Minister Chernomyrdin in late 1993, the Russian Federation and the United States of America decided to undertake the Joint Electric Power Alternatives Study (JEPAS). The goal of JEPAS was to provide a time phased investment programme for the period 1995–2000 on the basis of an objective assessment of Russia's electric power production alternatives through the year 2010. The two scenarios, the 'optimistic' scenario A and the 'pessimistic' scenario B, considered in this study (Fig. 3) were based on two views of Russian economic performance and electricity demand, set forth in the Russian Energy Strategy (Main Directions), and on a set of assumptions regarding the pace and the degree of success of measures for controlling inflation and reforming the economy. The financing requirements were calculated from the total costs of investments, and the potential domestic and foreign sources of finance were identified.

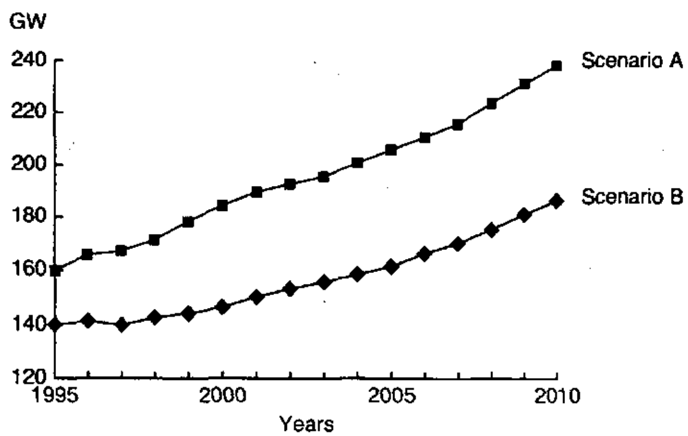

FIG. 3. Scenario A ('optimistic' scenario) and scenario B ('pessimistic' scenario) considered in JEPAS.

Five working groups of experts from Russia and the USA were formed in order to develop the information needed to complete this evaluation: Working Group 1 prepared an evaluation of the economics of the range of demand side investment options. Working Group 2 analysed the costs of modernizing existing fossil fuelled thermal power plants and investing in new fossil fuelled power plants. Working Group 3, which considered the Russian NPPs, worked separately and made independent studies concerning the nuclear power economy. This group evaluated the economics and the feasibility of certain safety improvements of NPPs, assessed the decommissioning requiremens for NPPs, evaluated the repowering of partially built NPPs, assessed the completion of such NPPs, and evaluated the construction of new, evolutionary NPPs. Working Group 4 assessed the feasibility and the economics of investment in transmission systems, power control and hydroelectricity. Working Group 5 prepared economic and electricity demand scenarios, addressed financing issues and integrated the results of the work in the other working groups.

4.2. Forecasting models

To determine the investment requirements of JEPAS, two planning models were applied which used the databases prepared by the working groups. The Russian simulation model, which uses the experience gained in planning for the power sector, based on heuristic knowledge and pre-feasibility studies, performs the following tasks: development of capacity and power balances on regional bases; determination of a preferred sequence of capacity buildup for various types of electric power plants, including reconstruction of existing power plants and construction of new plants; determination of the environmental impact of electric power plants and determination of investment requirements.

The US optimization model employs a formal, dynamic, linear programming cost minimization framework. The major features of this model are: accurate evaluation of inter-temporal trade-offs, explicit modelling of the trade-off between different modes of development of electric power supply, simultaneous optimization of electric power supply and demand side technologies to provide an integrated resource plan, and simultaneous cost minimization of electric power supply and heat supply.

In spite of some differences in their approach and criteria, the two models complemented each other and allowed systems analysis studies to be carried out, including a comparison of the economics of the different variants and alternatives for power sector development.

One of the most difficult tasks in this study was the conversion, from Russian local prices to world market prices, of the cost evaluations for the modernization of Russian NPPs; two different methods of cost evaluation were used. In the first method, the energy and economic database (EEDB), developed by US experts, was utilized as the basis and format for development of the cost estimates required for this study. The EEDB was selected for this purpose because of its unique capability to achieve consistency and comparability in a variety of cost estimates for dissimilar scenarios. The EEDB cost data models are based on quantities (e.g. materials and related installation hours), reflecting the specific design features of the US power plant models described in the technical database. The EEDB technical data are based on historical power plant designs; in addition, they are periodically checked against actual field data to ensure compatibility with current technical practice and cost experience in the USA. The direct costs are estimated in terms of quantities and prices of commodities, equipment and installation labour that reflect the design features of the power plant of interest. The EEDB method reflects the construction practices, wages, equipment costs and commodity prices in the USA. Thus, it is necessary to establish adjustment factors for converting the economic conditions reflected in the EEDB to Russian economic conditions and construction practices.

The second method was based on the ratios of Russian prices to world prices (1990) for specific kinds of product. Using the sectorial input–output model developed by the Central Economic–Mathematical Institute of the Russian Academy of Sciences, aggregated ratios were developed for the basic components of construction costs of power plants.

4.3. Conclusions and recommendations

The JEPAS analysis indicates the following ranking of priorities for the period 1995–2000:

- Improvements in the efficiency of electricity end-use;
- Nuclear safety upgrades, particularly for first-generation nuclear power reactors approved by the regulatory authority;
- Further development of the IPS through expansion and strengthening of inter-regional and intra-regional transmission, particularly between regions having a surplus of electricity and regions having a deficit of electricity, and modernization of control/dispatch centres;
- Modernization and rehabilitation of thermal power plants, using improved technology, with consideration of life extension options;
- Completion of NPPs that are at advanced stages of construction;
- Construction of new gas fired plants of the simple cycle type and the combined cycle type;
- Completion of detailed design for new-generation NPPs to enable their certification by the regulatory authorities.

Full rehabilitation of thermal power plants scheduled for retirement will play a significant role in meeting future power needs; however, the investment costs for rehabilitation are significant. Extension of the plant life provides an opportunity to reduce the required investments for the period under consideration. Therefore, plant-level evaluations of rehabilitation and life extension options for thermal power plants are recommended.

It was found in JEPAS that investments for safety upgrades of NPPs are comparable with investments in alternative power sources. It is considered to be economic to continue operation of most of the existing NPPs after completion of the safety upgrades evaluated in this study and after approval by the nuclear regulatory agency, Gosatomnadzor. Implementation of such safety upgrades may encourage foreign investment in Russia's nuclear power sector. In the initial study period, investments in safety upgrades of existing NPPs were considered as a priority, regardless of whether the increase in electricity demand is high or low.

Establishment of new nuclear capacity was found to be an economic supply option in some regions. Completion and commissioning of Rostov-1 and Kalinin-3 were identified as priorities for investment.

The amount of electricity generated from natural gas is expected to rise significantly under both scenarios because this type of electricity generation, using combined cycle and simple cycle technologies, is economically competitive in many regions of Russia.

The production of electric energy by NPPs will increase according to both scenarios. A further decline in the consumption of coal is expected.

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POLICY OPTIONS TO LIMIT CO_2 EMISSIONS FROM ELECTRICITY SUPPLY
*An OECD perspective**

J. ELLIS, S. PEAKE
Energy and Environment Division,
International Energy Agency,
Paris, France

Abstract

POLICY OPTIONS TO LIMIT CO_2 EMISSIONS FROM ELECTRICITY SUPPLY: AN OECD PERSPECTIVE.

The paper gives an overview of policy measures that countries within the Organisation for Economic Co-operation and Development (OECD) are pursuing in order to limit CO_2 emissions in the electricity sector, concentrating on policies used to influence fuel options in electricity production. The context in which these policies are intended to apply is changing rapidly because of structural and regulatory reforms, technological advances in capacity and fuel efficiency, increasing electricity demand and environmental pressures. OECD countries exhibit a wide variation in fuel mix for electricity supply. This is reflected in the CO_2 intensity of electricity production, which has declined in recent years to an average of 462 g CO_2/kW·h in 1993 (but there are variations from 1 to 2005 g CO_2/kW·h in different OECD countries). The changes in fuel mix that have led to this decline are affected by political, economic, environmental and employment factors as well as by consumer pressure. Electricity policies attempt to simultaneously balance these often conflicting demands. In the case of renewable energy, which almost all OECD Governments are promoting to a greater or lesser extent, a wide range of policies have been put in place. One of the more common policies is a guaranteed market or price for a certain amount of renewable electricity, although voluntary agreements between two or more interested parties are becoming more widespread. However, it is difficult to evaluate the effectiveness of different policy mixes, many of which were introduced only recently, because achieving a short term increase in renewable electricity via discrete and/or limited Government support may not be enough to lead to a durable increase in this energy source. The effect of deregulation adds a further uncertainty.

* The views and opinions expressed in this paper are those of the authors and do not reflect any official position of the International Energy Agency or of the Organisation for Economic Co-operation and Development.

1. INTRODUCTION

The framework affecting international energy policy, and especially electricity, is changing rapidly, for several reasons.

Consumption of electricity worldwide is projected to grow at a faster rate than is consumption of any other fuel. Electricity demand in countries within the Organisation for Economic Co-operation and Development (OECD) is set to grow at up to 2.1% p.a. until the year 2010 [1] — a much lower growth rate than previous ones in the 1960s and 1970s and the annual growth rates of 6% demonstrated by Asia, but higher than the growth rates for coal, oil or natural gas. The importance of electricity in the energy use of OECD countries is projected to increase from its current level of almost 18% to over 21% of the total by the year 2010. This general figure masks sectoral dependence on electricity, which approached 30% for the residential sector in 1993 and 43% for the commercial/public energy demand in the same year.

The **structure and regulation** of the electricity industries throughout the OECD countries is undergoing a period of rapid change, characterized by increasing deregulation and the unbundling and privatization (current or planned) of many State owned electricity companies [2]. Competition in electricity supply is therefore becoming more widespread. Utilities are also increasingly diversifying their activities beyond traditional lines and are putting greater emphasis on the quality of service provided.

Technological advances in electricity generation, such as increased efficiency, size (for renewable electricity generation) or reliability, are leading to a greater choice of plant types that can produce electricity at reasonable cost. This may affect the choice of fuels used for electricity production and/or the means of electricity generation from those fuels.

Local, regional and global **environmental issues** also exert forces that shape the policy context. Among the most prominent issue in OECD countries is the greenhouse effect, as all OECD countries except Mexico have environmental commitments relating to the emissions of greenhouse gases (GHG) under the United Nations Framework Convention on Climate Change (FCCC). As a consequence, the majority of OECD countries have initiated targets aimed at reducing, stabilizing or limiting growth in CO_2 and/or other GHG emissions.

Electricity supply is an important source of CO_2 emissions, accounting for 33% of the total OECD energy related CO_2 emissions in 1993. The total emissions from this sector are expected to grow as electricity demand increases. Fortunately, there are several actions that can reduce CO_2 emissions from electricity generation.[1] These can be divided into two groups: domestic and international. Domestic

[1] Increased cogeneration and/or replacing the direct use of fuels by highly efficient electrotechnologies could reduce emissions from the energy sector although it would raise emissions from the electricity sector. These possibilities will not be examined further here.

actions include promoting more efficient electricity production (e.g. upgrading simple cycle to combined cycle gas turbines); more efficient end-use technologies; electricity conservation or a change in the fuel mix used for electricity generation. This paper emphasizes *domestic* policy measures that OECD countries can pursue in order to limit CO_2 emissions in the electricity sector, and concentrates on policies that can or have been used to influence changes in the fuel mix used in electricity production.

International actions include increasing electricity imports and, potentially, 'actions implemented jointly' (AIJ — formerly known as joint implementation)[2]. Since many OECD countries have set up GHG commitments at the national level, i.e. relating to emissions on national territory, increased electricity imports could also be used as a tool for reduction of domestic emissions (if electricity imports were to replace fossil fired electricity generation). However, this would not necessarily result in reduction of global emissions.

The concept of AIJ was set out in the FCCC and involves countries undertaking emission reduction projects in other countries in exchange for credits that could be offset against domestic emissions. This is not yet a widespread possibility[3] because AIJ is currently in a pilot phase. However, some OECD countries — notably the United States of America, the Netherlands and the Scandinavian countries — are showing great interest in AIJ, not only as a potential means of satisfying emission reduction criteria but also as a way of exporting domestic environmentally friendly technologies to growing markets.

2. INFLUENCING THE FUEL MIX

Changes in the fuel mix for electricity supply will depend on the energy and electricity policy context, as well as the availability of alternative energy sources and the development of the necessary infrastructure. The current variation in fuel mix among OECD countries could hardly be wider: Norway, for example, currently generates 99% of its electricity from renewables; Denmark uses coal for 87% of its electricity (the United Kingdom, the USA, Australia and Germany also rely on coal for the majority of their electricity generation), France relies on nuclear power for over three quarters of its electricity supply, while oil is used for generating the majority of electricity in Italy. Table I illustrates these variations via the differing CO_2 intensity of electricity production.

Table II shows the CO_2 emissions from selected plant types, together with their expected cost of electricity generation in the year 2000. This table shows that

[2] Those interested in AIJ are directed to another body of work under way at the IEA.

[3] To date, only the USA has put an emission crediting scheme in place.

TABLE I. CHANGES IN THE RELATIVE IMPORTANCE OF FUELS IN OECD COUNTRIES, 1993–2000 [3, 4]

	Electricity intensity[a]	Coal	Oil	Gas	Nuclear	Geothermal	Solar, tide, wind, etc.	Combustible renewables	Hydro
Australia	806	⇑	⇓	⇓	—	—	—	—	⇓
Austria	194	⇑	⇓	⇑	—	—	—	⇑⇑	↑
Belgium	325	⇓	⇓	⇑	↑	—	≈	≈	⇑
Canada	176	↑	⇑	⇑	⇑	—	↑	⇑⇑	↑
Denmark	836	⇓	⇓	⇑⇑	—	—	⇑	⇑⇑	—
Finland	287	↑	⇑	⇑	↑	—	—	⇑	↓
France	58	⇑	⇑	⇑⇑	↑	—	—	↓	↑
Germany	640	↑	↓	⇑	↓	—	⇑⇑	⇑	⇑
Greece	932	↑	↓	⇑⇑	—	—	⇑	—	⇑
Iceland	1	—	—	—	—	⇑	—	—	⇓
Ireland	746	↓	⇑	↑	—	—	⇑⇑	—	↑
Italy	518	⇑	↓	⇑	—	↓	⇑⇑	⇑	↑
Japan	376	↑	↓	⇑	≈	⇓	⇑⇑	⇑	⇓
Luxembourg	2005	—	—	⇑⇑	—	—	—	—	↑
Mexico	513	Not available							
Netherlands	585	⇓	—	↑	⇓	—	⇑⇑	⇑⇑	⇑⇑
New Zealand	116	—	—	⇑	—	⇓	—	—	≈
Norway	2	↓	—	—	—	—	—	—	—

TABLE I (cont.)

Portugal	552	↑	⇓	—	—	—	⇑⇑	↑	⇑
Spain	417	↑	↑	⇑⇑	↓	—	—	⇑⇑	⇑
Sweden	46	⇓	⇑⇑	⇑⇑	⇑	—	⇑⇑	⇑⇑	↓
Switzerland	9	⇑	⇓	⇓	—	—	⇑	⇓	↓
Turkey	522	⇑	⇓	⇑	—	↑	—	—	↑
UK	551	↑	⇑	⇑⇑	⇓	—	⇑⇑	⇑⇑	↑
USA	570	↑	↑	⇑	↑	⇑	⇑⇑	⇑	⇑

[a] Grams CO_2 per kilowatt-hour.

↑ = growing electricity generation, but not as fast as the overall (total) electricity generation from all sources (↓ = somewhat lower).

⇑ = electricity generation projected to grow faster than the overall rate of electricity generation (⇓ = lower).

⇑⇑ = much faster growth, ⇓⇓ = much lower growth.

≈ and ~ = approximately stable; — = fuel is not used for electricity generation.

TABLE II. PROJECTED COSTS OF AND CO_2 EMISSIONS FROM SELECTED ELECTRICITY GENERATING SOURCES [5]

	Net efficiency (%)	Cost in the year 2000 (US ¢/kW·h)	CO_2 emissions[a] (g/kW·h)
Pulverized coal	36–43	4.0–6.5	795–950
Atmospheric fluidized bed combustion	36–43	4.8–5.3	795–950
Pressurized fluidized bed combustion	40–45	4.9–5.1	760–850
Integrated gasification coal combustion	44–49	4.9–5.1	700–775
Combined cycle gas turbine	50–61	3.7–7.3	330–405
Light water reactor	—	5.6–7.4	0
Large hydro	—	3.8–8.7	0
Centralized photovoltaic system	—	11.3–62.8	0
Geothermal	—	2.4–4.9	0
Wind	—	4.4–7.6	0
Large biomass	—	7.5–7.8	0

[a] Emissions from generation only (life cycle emissions not included).

a trade-off will still often be required in 2000 between low cost and low CO_2 emitting electricity generating technologies, despite the projected fall in the cost of renewable electricity. Recent moves towards less carbon intensive fuels are presented in Table III, which clearly shows the increasing proportion of non-carbon fuels and the decreasing CO_2 intensity of OECD electricity supply since 1985. The importance of non-carbon fuels is projected, however, to drop slightly until the year 2000, as growth in electricity production from nuclear and hydro sources will be outpaced by total electricity growth (Table I), with the largest growth rates for most OECD countries being for electricity generation from solar and wind energy (which at present generate the smallest quantity of electricity), followed by natural gas[4].

[4] Coal is also shown as growing rapidly in six countries. However, three of these countries use a small amount of coal for shoulder purposes only, with Switzerland continuing to use coal as a reserve.

TABLE III. FUEL MIX IN OECD ELECTRICITY GENERATION (%) IN 1985, 1990, 1993 AND 2000 [3, 4]

	1985	1990	1993	2000
Coal	41.5	40.21	39.20	37.41
Combustible renewables	0.2	1.19	1.40	2.03[a]
Oil	9.0	8.72	6.9	6.21
Gas	9.7	10.41	11.54	15.28
Nuclear	20.1	23.03	24.17	22.38
Hydro	19.1	16.03	16.36	15.35
Geothermal	0.3	0.33	0.34	0.33
Solar, wind, tide	0.01	0.07	0.09	1.01
Total non-carbon fuels	39.7	40.65	42.36	41.1
Total	100	100	100	100
Total CO_2 from electricity generation (Mt CO_2)	3080	3391	3517	—
CO_2 intensity (g CO_2/kW·h)	506	471	462	—

Note: Mexico excluded. Totals may not add because of rounding.

[a] Peat is included in coal for historical data and in combustible renewables for forecast.

Possibilities of GHG emission reductions in electricity supply as well as the GHG commitments of Parties to the FCCC have led some of them to reduce the carbon intensity of electricity generation, i.e. by increasing the importance of nuclear power, natural gas or renewables. The policies in place to reach these objectives are diverse and are reflected in the programmes undertaken by IEA member countries.

3. GOALS FOR THE DOMESTIC ELECTRICITY POLICY

The fuel mix used in electricity generation will be affected by energy related and non-energy related factors, including economic factors, employment issues, consumer pressure and environmental concerns. The relative importance of these factors may change with a change in the structure, regulation and ownership of the domestic electricity supply industry (Fig. 1).

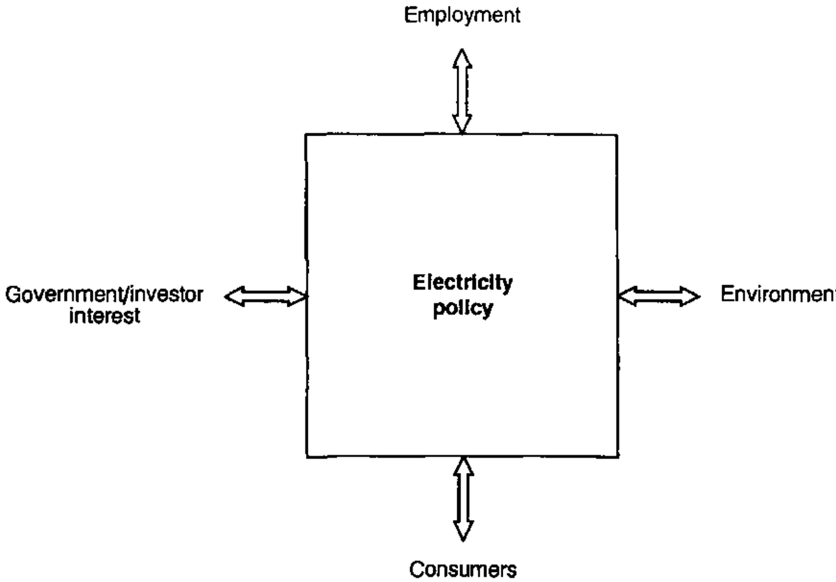

FIG. 1. Factors influencing the electricity policy.

The importance accorded to each factor by Governments will differ from country to country and will alter over time. A country with a large domestic mining industry and large reserves of coal may wish to include this fuel as an important source for electricity generation, even if it is more expensive and more CO_2 intensive than alternatives, in order to keep a certain level of employment in mining industries. Governments may therefore accept and/or subsidize a higher domestic electricity price in order to maintain tax receipts or to reduce social security payments (e.g. for unemployment). However, a trade-off has also to be made between supporting expensive indigenous fuels and/or clean fuels and maintaining international competitiveness.

The interest of private electricity generating companies in achieving a high rate of return may, for example, reduce their willingness to invest in pollution abatement technologies or generating technologies with a high capital cost. Changing the pattern of private/public ownership of the electricity industry may therefore alter the fuel and/or technology choices made and, through that, the environmental performance of the sector. Public opinion may also influence the fuel mix via political pressure to initiate or discontinue certain programmes.

Consumers are generally interested in obtaining a cheap, clean and reliable electricity supply. So far, consumers faced with a monopoly domestic producer have had little opportunity to exercise a choice of electricity suppliers. However, increased competition in electricity supply (from domestic producers, the electricity trade and perhaps eventually widespread retail wheeling/third party access) arising from changes in the structure and regulation of the electricity supply industry in OECD countries could enable consumers to choose an electricity supplier. This has led to some concern amongst environmental groups in some countries that the widespread advent of retail wheeling could lead to power generation being concentrated in large, cheap (and generally fossil fired) units, which would be against domestic commitments relating to CO_2 emissions. Some generators are also concerned that retail wheeling might lead to 'stranded' investment costs (although restructuring proposals made to date have favoured recovery of stranded costs). Conversely, some consumers may be prepared to pay a premium for 'green electricity' if given adequate information — a possibility that is being actively explored in a pilot programme in the Netherlands and embodied in the restructuring proposal of the Californian power sector.

Environmental issues and commitments such as those relating to future levels of GHG emissions are another factor that may need to be taken into account when trying to influence fuel choice decisions. This is in turn influenced by the nature of commitments: binding legislation, regulations with disincentives for non-compliance and negotiated agreements are more likely to be upheld than non-binding targets (although 'free rider' problems may arise if negotiated agreements do not encompass all actors in, for example, electricity supply). This was seen when a number of IEA countries failed to meet highly ambitious but non-binding targets for the introduction of different renewable energy sources.

3.1. Policy context

In 1993, the 23 IEA countries[5] adopted a set of Shared Goals that "... seek to create the conditions in which the energy sectors of their economies can make the fullest possible contribution to sustainable economic development and the well-being of their people and of the environment". More specifically, these goals include the desire for diverse and secure energy supplies; environmentally sustainable provision of energy; encouragement of the use of environmentally acceptable energy sources; continued research, development and deployment of new and improved energy technologies; and undistorted energy prices. This section examines the trade-offs that Governments make in order to balance economic, environmental and energy objectives.

[5] Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, UK and USA.

In OECD countries there is currently a move towards electricity market liberalization and deregulation; although some OECD countries such as France, Greece and Ireland still have State owned vertically integrated electricity companies, other OECD countries have deregulated, unbundled or privatized their electricity industry and more countries are indicating that they will follow a similar route. Deregulation and privatization are leading to increased competition in electricity supply, and internationalization of the electricity supply industry is also becoming more important, either via electricity trade or via non-local ownership of electricity generators.

Many IEA Governments therefore have less direct influence on the electricity supply industry now than a decade ago. Nevertheless, they still try to simultaneously balance the often contradictory goals in electricity supply (as shown in Fig. 1), namely:

— Use of higher cost (or dirtier) domestic fuels or of lower cost (or cleaner) imported fuels;
— Higher short term cost of electricity supply from renewable energy sources versus their long term sustainability potential;
— Non-CO_2 aspects of nuclear power versus public perception of nuclear power as unsafe;
— Balancing profits of electricity companies with electricity conservation and efficiency and various forms of negative externalities.

3.2. Policy options

Policy options that Governments could use to influence the fuel mix in a country range from 'command and control', such as fuel use requirements, economic instruments and emission limits or standards, to more consensus building/persuasive instruments, such as voluntary agreements, incentives and R&D. Major actions taken to date have included:

— Loosening the restriction on natural gas use for power generation in countries within the European Union and in the USA; this, when combined with increasing competition, has led to the increase in natural gas use;
— A political decision by some countries to discontinue nuclear power programmes;
— Deregulating and unbundling the electricity supply industry.

In the majority of OECD countries, policies have also been put in place to promote renewable energy. These policies merit further examination, since, although non-hydro renewables are projected to be the fastest growing source of electricity generation, they also account for the smallest proportion of electricity production to date (and their proportion will remain small even if these policy objectives are achieved — see Table I). Most countries cite environmental objectives (i.e. GHG commitments or local air pollution issues) as a reason for wishing to promote renewables, although fuel diversity/energy security is an important stated criterion for Italy, Japan, New Zealand, Spain, Turkey and the UK.

The policy measures in OECD countries to encourage renewable electricity include taxes, grants, capital or output subsidies, guaranteed markets, voluntary approaches, R&D and renewable energy targets. These are listed for selected OECD countries in Table IV.

Policies to promote non-hydro renewables were typically introduced at the beginning of the decade and have had some success to date, with a sharp rise in electricity generated from combustible renewables and a small rise in solar and wind electricity. The mix of policies in place in each country generally includes both 'command and control' type instruments and consensus building/persuasive programmes. However, both sets of policies are often in direct contradiction to stated national or international aims (such as the shared goals mentioned above).

For example, Government intervention that guarantees a market for a certain amount of higher priced renewable electricity, as in the UK's Renewable Order under the non-fossil fuel obligation (NFFO), distorts the electricity market and as such is opposed to the general policy direction of increasing the importance of market forces in that country. However, the NFFO was designed to run for a limited time period only and aims at reducing the environmental effect of electricity in the longer term by encouraging commercialization of certain renewable energy sources. It is paid for via a levy on consumer bills. Similar schemes are in place in other countries, such as Canada and Ireland, although, in all three countries, only limited increases in renewable electricity capacity are encouraged. Preferential power purchases may even be ruled unconstitutional in some OECD countries.

The unilateral introduction of carbon taxes (although favouring non-carbon energy) could reduce the competitiveness of the domestic industry and/or reduce domestic demand for indigenous fuels. This would adversely affect economic growth, employment and energy security and is the reason why so few countries have introduced such taxes (and have often granted exemptions or reductions to large users when such a tax is in place).

Negotiated policies such as voluntary agreements may reduce the 'pull' on electricity policy in any one of the four directions shown in Fig. 1, since such policies represent a negotiated position between two or more interested groups and as such are likely to represent a certain degree of compromise. Voluntary agreements are an example of such an approach that is being introduced in OECD countries. Voluntary agreements in nine OECD countries include measures to increase electricity generation from renewable sources[6]. The procedure followed in setting up

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[6] Voluntary agreements have been introduced by Austria, Norway and Switzerland in addition to the countries shown in Table III.

TABLE IV. POLICY MEASURES TO PROMOTE RENEWABLE ENERGY IN SELECTED OECD COUNTRIES

	Information, education and exhortation programmes[a]	Financial incentives for investment in renewable technology[b]	Regulatory measures and standards[c]	Voluntary agreements	Electricity supply industry	
					Output/ capacity targets or quotas	Favourable or guaranteed market
Australia	✓ 1	✓ 2, 3 (ethanol)				✓ (voluntary)
Belgium	✓ 1 (region)	✓ 1, 2, 3, 4	✓ 4 (building codes)			
Canada		✓ 1, 3	✓ (mapping)		✓	
Denmark		✓ 1, 3	✓ (survey requirement)	✓	✓	✓
Finland	✓	✓ 1, 3			✓	
France	✓ 1, 4	✓ 2 (overseas territories), 3	Waste regulations	✓		✓
Germany	✓ 4	✓ 1	✓ (building codes)			✓
Greece	✓					✓ (bilateral)
Ireland		✓ 4 (buy-back rates)	✓ Partnership Government programme		✓ Capacity	✓
Italy		✓ 1, 4	✓		✓	✓
Japan	✓ 2, 3	✓ 1, 2	✓ (reducing planning barriers; guidelines for grid-connected systems)	✓		✓ purchasing menu

Netherlands	✓ 3	✓ 1, 3		✓	✓	✓
New Zealand	✓ (advice to planners)	✓ 3		✓		✓
Spain		✓ 4 (3rd party)			✓	✓
Sweden	✓	✓ 1, 3	✓ 1			✓
Turkey					✓	
UK	✓	✓ 1	✓ (Waste disposal standards)	-	✓	✓
USA	✓	✓ 1,3	✓	✓		✓

Source: Ref. [4].

[a] Information, education and exhortation programmes:
1 - Publications, advertising campaigns;
2 - Courses for industry;
3 - Education programmes in schools and workplaces;
4 - Renewable energy advice centres;
5 - Others.

[b] Financial incentives:
1 — Grants and subsidies involving direct transfers;
2 — Credit instruments (interest rate loans, soft loans, loan guarantees);
3 — Tax exemptions (tax reliefs, credits, deferrals);
4 — Others.

[c] Regulatory measures and standards:
1 - Planning/siting legislation;
2 - Environmental impact assessment;
3 - Compulsory legislation for utility compliance, e.g. purchase price guarantees;
4 - Others (building codes).

voluntary agreements and their degree of 'voluntarity' varies by country. For example, in some countries and sectors voluntary agreements allow self-setting and monitoring of targets, while in other countries such agreements are more formal, negotiated 'voluntary agreements' that are binding when they are signed. The US Climate Challenge Programme is an example of a voluntary approach between the Department of Energy and a utility (as no utility has to join), whereas the Dutch A MAP II agreement with the electricity distribution companies, whereby they undertake to produce 3% of electricity from renewable sources, is an example of a voluntary agreement.

4. CONCLUSIONS

OECD countries can progress towards their GHG commitments in many ways, including increased end-use efficiency, energy conservation, cogeneration, electricity trade, promoting more efficient electricity production and, potentially, AIJ. Another option is to decrease the carbon intensity of electricity generation via a switch to less carbon intensive fuels.

The CO_2 intensity of electricity generation has been decreasing steadily because of the increased importance of nuclear power and gas fired electricity, as well as the technological improvements in fossil fuel electricity generation, although reducing GHG emissions was not the driving force behind the policies that led to these trends. The shift to combined cycle gas turbines in some deregulated markets will in any case reduce the CO_2 intensity of electricity to a certain extent. The current GHG commitments of OECD countries have acted as an impetus for many countries to introduce policies that would further reduce the carbon intensity of electricity generation. These policies often concern the promotion of renewable electricity (since other factors may constrain nuclear power expansion and the economics of gas fired generation ensures it needs little promotion).

Policies vary by country, but they aim at balancing conflicting demands of different groups, taking into account the fact that large or sudden changes in the fuel mix often meet resistance because of increased or decreased pressure from groups regarding economic or employment issues, environmental emissions and/or safety, and perceived effects on international competitiveness and/or energy security.

The overall shape of policies is determined by increasing electricity demand, the changing structure of the electricity supply industry, technological innovations and the declining Government intervention in electricity supply (with greater competition leading to a downward pressure on costs).

Policies recently put in place include instruments such as a guaranteed market or a guaranteed minimum price for renewable electricity, voluntary agreements between two or more interested parties, as well as investment incentives, regulatory measures, information programmes and R&D. The importance of renewable electricity has risen slightly since these programmes were put in place and is projected to continue doing so. However, it is difficult to evaluate the effectiveness of different policy mixes, many of which were introduced recently, because achieving a short term increase in renewable electricity via discrete or limited Government support may not be enough to lead to a durable increase in this energy source. Deregulation adds a further uncertainty.

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THE PROCESS OF BUILDING CONSENSUS IN POWER DEVELOPMENT
A methodology for the involvement of indigenous people in decision making

R. LANARI
Makivik Corporation,
Lachine, Quebec, Canada

Abstract

THE PROCESS OF BUILDING CONSENSUS IN POWER DEVELOPMENT: A METHODOLOGY FOR THE INVOLVEMENT OF INDIGENOUS PEOPLE IN DECISION MAKING.

The paper is a contribution to the advancement of methodologies for comparative assessment; it outlines the procedures for participation and decision making developed by the Inuit of Nunavik, Canada, with respect to the Grande-Baleine hydroelectric project. The key issue of indigenous involvement in decision making processes related to energy production is dealt with by examining the methodology developed in connection with a hydroelectric project. While this type of project has its own specific issues, which are related to the use of the land, and the social, environmental and economic impacts, the methodology developed could be adapted to any energy production project. The paper gives the World Bank definition of 'consultation' and shows that the Inuit attempted to apply this concept to the present situation and even to enlarge its scope. The Inuit and their region are described first; then the Grande-Baleine environmental assessment process as well as the negotiations of the Inuit with Hydro-Québec are summarized; finally, the decision making flow which led to a final consensus is delineated.

1. INTRODUCTION

This paper is a contribution to the advancement of methodologies for comparative assessment; it outlines the procedure for participation and decision making developed by the Inuit of Nunavik (Canada) regarding the Grande-Baleine hydroelectric project. The Grande-Baleine environmental assessment process is summarized first; it evolved as a result of agreements between the two levels of jurisdiction (federal/provincial) and the indigenous groups involved, the Cree Indians and the Inuit. Then, through an analysis of the Inuit involvement in this process, the decision making flow that led to a final consensus on the Grande-Baleine project is delineated. Finally, a preliminary assessment of the methodology developed is given.

Environmental assessment and decision making among the Inuit are two interrelated and complementary aspects which can hardly be dissociated. In order to fully understand both, however, we need to consider each of them separately, always keeping in mind interactions and feedback effects. Also, one must not forget that the Quebec Government has final authority as regards implementing the Grande-Baleine project or putting it on hold, as will be seen. When the project was launched, the Inuit participated in the environmental assessment, including justification and design of the project, as well as its social and environmental impacts.

This involvement in the environmental assessment is part and parcel of what is usually termed 'public consultation'. In a participatory democracy, consultation of the populations most affected by a development project is now common practice. The term 'consultation' can be defined in many ways; we have chosen the definition used by the World Bank, as it emphasizes the influence people can exercise on decision making. This definition reads as follows:

> "A process by which people — especially disadvantaged people — can exercise influence over policy formulation, design alternatives, investment choices, management, and monitoring of development intervention in their communities." (Ref. [1], p. 2).

We have attempted to apply this definition to the given situation and even to enlarge its scope. Indeed, the Inuit were not only involved in the public decision making process through the environmental assessment procedures — which were open to all — but they were also able to negotiate with Hydro-Québec a separate agreement encompassing every aspect of the project, including project justification and description, social and environmental impacts, mitigative measures, environmental follow-up and financial compensation.

It is appropriate here to give some background information about the Inuit and the Grande-Baleine project from 1971 onwards.

2. THE INUIT

Nunavik (Fig. 1) — the Arctic region of Quebec lying north of the 55th parallel — is inhabited by an almost exclusively Inuit population of some 7000. The Inuit live in 14 communities of between 120 and 1500 people.

With a land area in excess of 480 000 km^2, Nunavik is an immense territory where there are no roads, the communities being linked with each other and with Southern Quebec only through one regional airline. Starting in the 1950s, the process of transition from a nomadic to a settled way of life led to large changes within the Inuit society, bringing about a transition from a subsistence economy, centred on hunting, fishing and trapping, to a mixed economy, with wage earning playing an increasing role. New, foreign values were superimposed on nature oriented traditional values.

The Inuit now must face tremendous challenges, with few alternatives. Given this context of a rapid, externally driven change, the implementation of a hydroelectric megaproject raises fundamental questions and widely shared concerns.

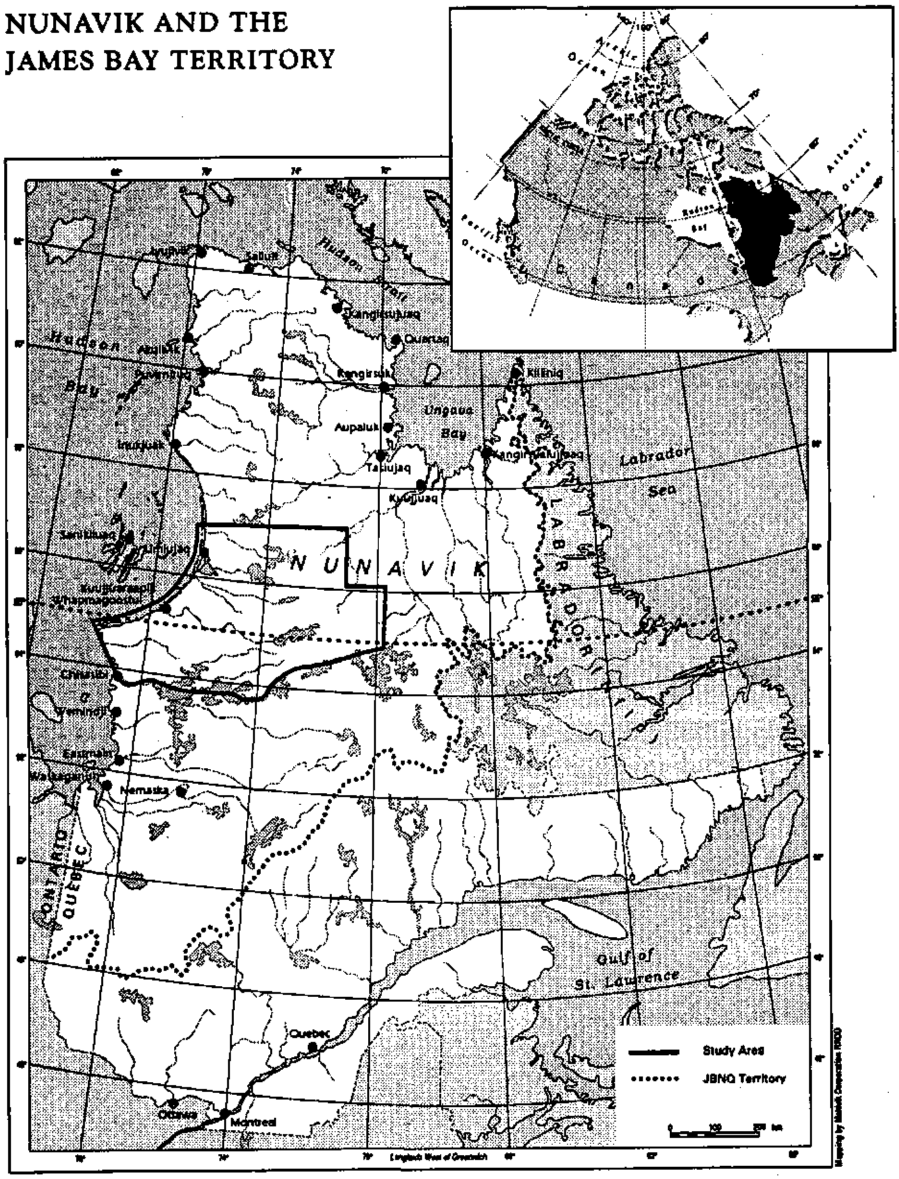

FIG. 1. Nunavik and the James Bay territory.

TABLE I. SEQUENCE OF EVENTS

General background

1971: Announcement of the James Bay project
1975: James Bay and Northern Quebec Agreement
1976–1982: Grande-Baleine project
1988–1994: Resumption of the Grande-Baleine project

Environmental assessment	**Inuit involvement**	**Negotiations**
1989: Splitting-up of the Grande-Baleine project's assessment	Legal action by Makivik	September 1990
Jan. 1992: Memorandum of Understanding for a single environmental assessment process	Inuit participation	Memorandum of Understanding signed in February 1991
Jan.–March 1992: Public hearings	Submissions by members of the communities and Makivik	
April 1992: Draft Guidelines on the Environmental Impact Study (EIS)	Comments from Makivik in June 1992	
Sep. 1992: Final Guidelines		
Aug. 1993: EIS by Hydro-Québec		
1993–1994: EIS analysis regarding conformity with Guidelines		
Sep.–Aug. 1993: Comments from stakeholders	Submission of Makivik's comments in July 1993	
Nov. 1993: Joint report on EIS conformity and quality		14 April 1994: Conclusion of Agreement-in-Principle

3. HISTORICAL BACKGROUND

3.1. The James Bay project

In 1971 the Government of Quebec decided to proceed with the James Bay hydroelectric project (Table I). At that time, there was neither public consultation nor environmental assessment, let alone negotiations. The population learned through the media that a megaproject was soon to be launched. In November 1972 the Indians of Quebec Association lodged a protest with the provincial Government, claiming aboriginal title to the land. The Crees and the Inuit, the two indigenous groups directly affected, filed an injunction request, asking the Court that all work be stopped, pending settlement of their land claims. In 1973 such a Court order was obtained, but after one week it was overturned by the provincial Court of Appeals.

Although the indigenous groups lost the judicial battle, they won a political victory, for the Government of Quebec agreed to undertake negotiations, which eventually (in 1975) led to the signing of a land claims settlement — the *James Bay and Northern Quebec Agreement* (JBNQA).

The JBNQA was a treaty within the terms of the Constitution of Canada, establishing an economic, political and legal framework for the James Bay and Nunavik territories. Under the JBNQA, the Crees and the Inuit were given financial compensation; moreover, far reaching rights were given to them and a variety of political and economic structures were set up, all of which were to be managed by and on behalf of the indigenous people.

Among the rights recognized, the JBNQA provided for an assessment of environmental and social impacts in the event of any development project on the territories covered. It also contained provisions enabling the Inuit, the Crees and Hydro-Québec to conclude agreements on mitigative measures in relation to future development projects.

Finally, in connection with the JBNQA, the Makivik Corporation was founded; it is responsible for promoting and protecting the rights and interests of its sole members and beneficiaries, the Inuit of Nunavik.

3.2. The Grande-Baleine project

As a follow-up to the James Bay project, Hydro-Québec undertook feasibility studies on the 3000 MW Grande-Baleine hydroelectric project. Two separate periods must be considered: from 1976 to 1982 and from 1988 to 1994.

In 1976, Hydro-Québec set up a Task Force that was responsible for circulating information to the Crees and the Inuit of Kuujjuarapik. Since this Task Force was not very efficient, the Grand Council of the Crees (of Quebec) recommended three years later that Hydro-Québec create a co-ordinating table for the purpose of reviewing all hydroelectric development projects with potential impacts on the Cree population. The Inuit followed suit in 1980, with respect to all future projects north of the 55th parallel. The Grande-Baleine project was of course part of the agenda. Discussions touched upon access strategies, road corridors, options for port facilities, airport locations and mitigative measures.

In 1982 the Grande-Baleine project was postponed. Research work, consultations and discussions were stopped, and thus the committees and co-ordinating tables lost all purpose.

Hydro-Québec revived the Grande-Baleine initiative in 1988. From that date onwards, events quickened, and we now come to the heart of the matter: first the environmental assessment structures set up by Governments and the role given to the Inuit therein; second the negotiation process; and third the flow of decision making among the Inuit.

4. ENVIRONMENTAL ASSESSMENT STRUCTURES

From the outset, Hydro-Québec submitted a tight schedule and proposed that the project be split up with a view to fast-tracking the environmental assessment process; work on roads and on the infrastructure would be assessed first, so that Hydro-Québec could go ahead with road construction while proceeding with the second-phase assessment of dams and dykes.

This proposal caused much controversy; this was the time when the Crees and the Inuit became involved in the decision making process with respect to environmental assessment.

The Crees took legal action before the provincial Supreme Court, seeking to nullify the splitting up of the project in order to enable environmental assessment. The Makivik Corporation followed suit, becoming party to the proceedings. The dispute was soon settled out of court, and Hydro-Québec announced that it would not split up the project. The question as to how the project as a whole would be assessed remained unclear.

Five committees, each with its own mandate and jurisdiction, were responsible for evaluating the project — a complex system that could have developed into a bureaucratic nightmare if no proper solutions were found. Moreover, the stakeholders had to have the financial means to participate meaningfully in such an evaluation process. The main parties — the Crees, the Inuit, Hydro-Québec and the two Governments — signed in January 1992 a Memorandum of Understanding, which included the following main provisions:

(1) The five committees would co-ordinate their actions so as to undertake a single environmental assessment process.

(2) The make-up of the committees would be better balanced and their members reduced from 27 (including 17 Government representatives) to 21, including ten representatives from the indigenous groups.

(3) A fund of Can $2 million (US $1 685 600) would be put at the stakeholders' disposal by the two Governments, with the Inuit share amounting to Can $666 666 (US $561 866).

(4) Hydro-Québec agreed to add Can $1.5 million (US $1 264 200) for the Inuit and to create a joint technical information exchange group with respect to project justification, with members from Hydro-Québec, the Inuit and the Crees.

The first task of the review committees was to draft guidelines for Hydro-Québec to be followed in its environmental impact study (EIS). Between January and March 1992, public hearings on the contents of the guidelines were held by these committees in the affected Inuit and Cree communities, as well as in Montreal, affording each stakeholder an opportunity to submit recommendations.

In every community, concerns, misgivings and fears were voiced in an impressive turnout. In March 1992 the Makivik Corporation submitted 87 recommendations on the contents of the guidelines. In April 1992 the review committees released Draft Guidelines, and Makivik commented on them two months later. Final Guidelines were issued to Hydro-Québec in September 1992.

Almost a year later, on 31 August 1993, Hydro-Québec filed its *Feasibility Study*, including the EIS; a summary in both Inutitut and Cree followed in February 1994 and an audiovisual presentation was made two months later. Finally, during an additional round of public consultations regarding the report on conformity with the EIS, Makivik submitted its own *Report on Conformity Analysis* in July 1994. Afterwards, the review committees released their *Joint Report on the Conformity and Quality of the Environmental Impact Statement for the Proposed Great Whale River Hydroelectric Project*, in November 1994.

5. NEGOTIATIONS

Parallel to the environmental assessment process, the Inuit and Hydro-Québec initiated a negotiation process in 1990.

Although this negotiation process related to the same matters, it created an altogether different dynamics: it provided direct access to higher authorities at Hydro-Québec; it opened up an alternative channel for the Inuit to identify, together with Hydro-Québec, the effective scope of project impacts and mitigation or minimization of potential impacts; and it allowed the Inuit to determine whether Hydro-Québec was ready to share the benefits flowing from the project, in a fair and equitable manner, with the Inuit from the communities that were most impacted by the project and with the Nunavik population as a whole. By entering into negotiations in a formal setting, both parties eschewed confrontational tactics, facilitating the exchange of data and views about project design and scheduling, social and environmental impacts, mitigative measures and financial compensation.

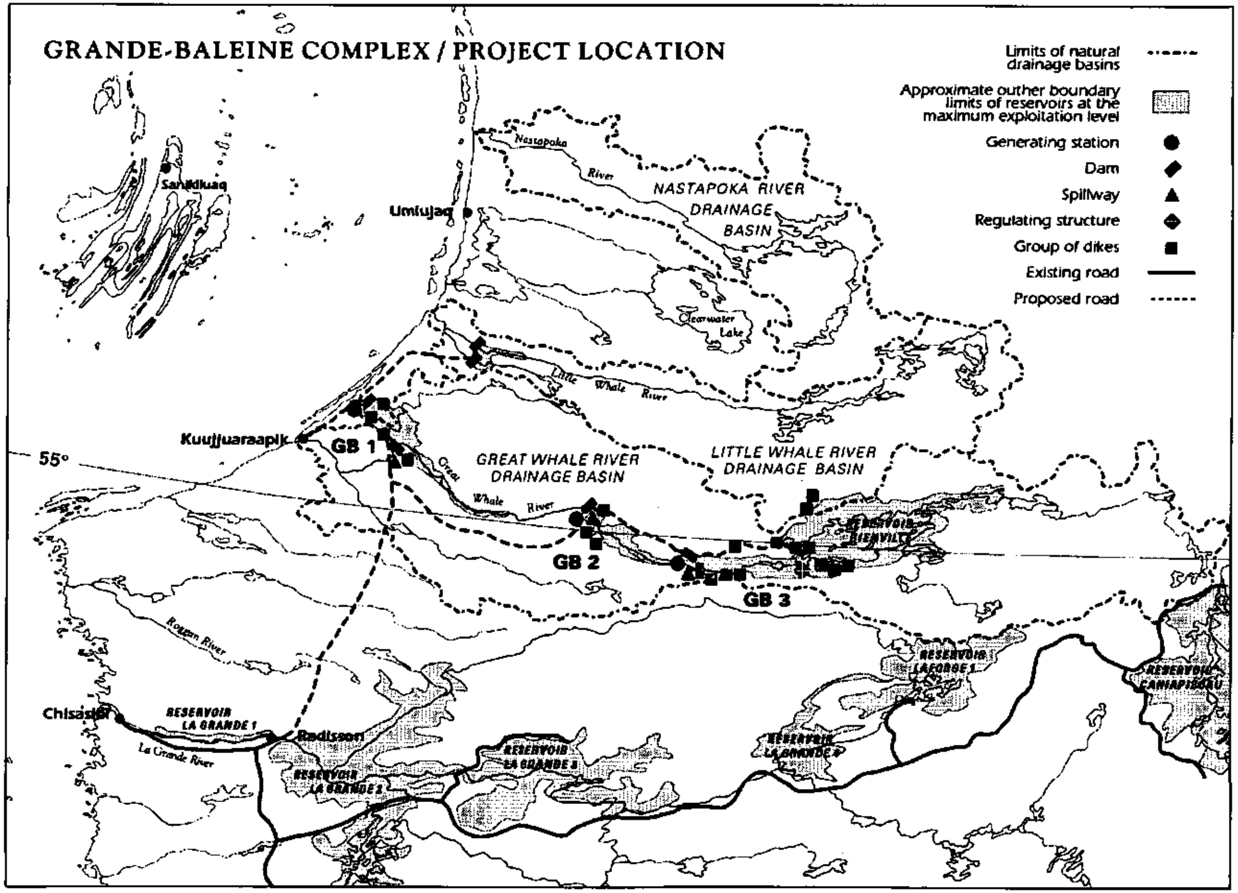

FIG. 2. Grande-Baleine complex — project location.

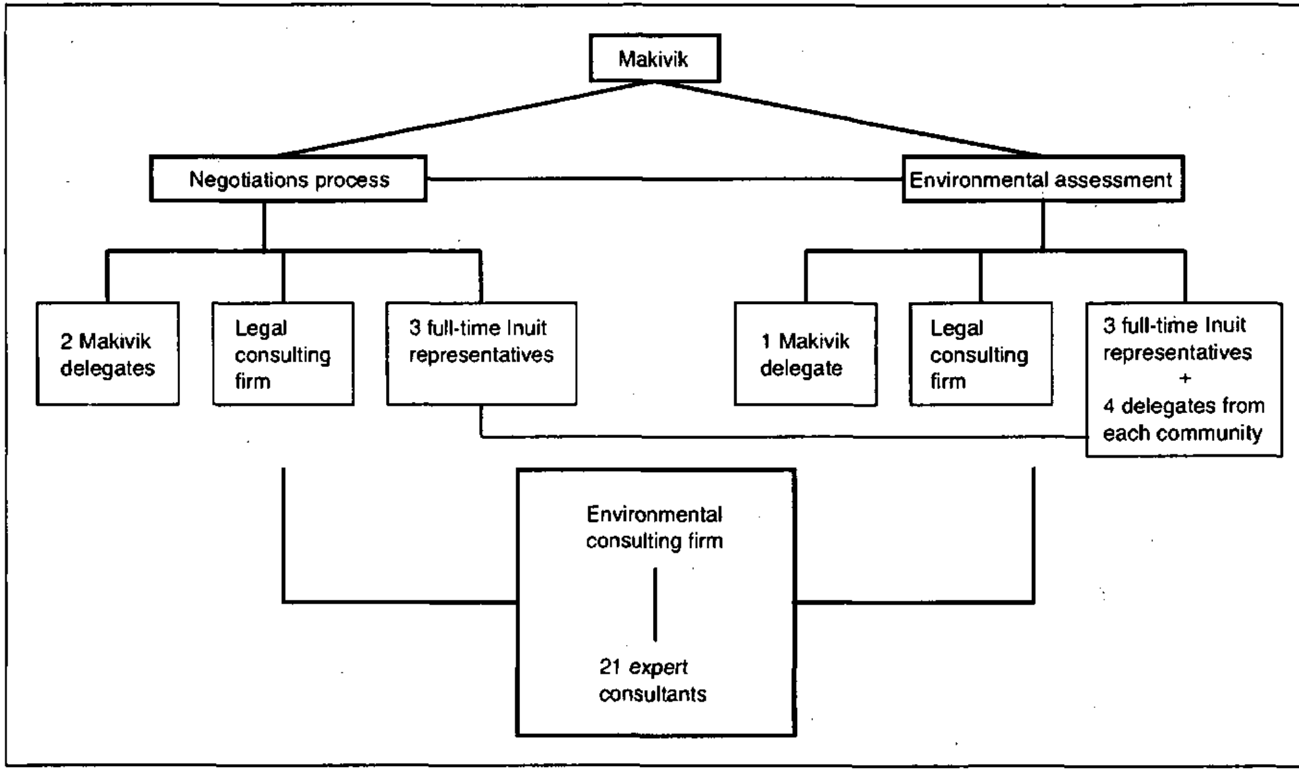

FIG. 3. *Team of Makivik delegates and Inuit representatives.*

The negotiation process allowed the Inuit to scrutinize Hydro-Québec's plans and to recommend changes. For instance, the preferred scenarios of Hydro-Québec included diverting a major river (Fig. 2), but this scenario was abandoned, mostly because of Inuit opposition as expressed during frank and open talks. Finally, in April 1994, both parties signed an *Agreement-in-Principle*, in which they undertook to negotiate and to agree upon the terms of a Final Agreement regarding employment, training, mitigative measures, financial compensations and other related issues.

For the purpose of this paper, the above considerations adequately outline the Inuit involvement in and influence on the parallel environmental assessment and negotiation processes. Now we turn to the specific methodology implemented among the Inuit, as seen from an inside perspective, that enabled such involvement and interaction.

6. DECISION MAKING AMONG THE INUIT

Prior to the implementation of the processes of environmental assessment and negotiations, Hydro-Québec and the Inuit had already agreed, early in 1989, to create a working group including four Inuit representatives for the purpose of circulating information among the Inuit population and acquiring feedback from it. The Inuit perceived this working group as affording an opportunity to update their knowledge and to ensure that the people would be properly informed.

When negotiations between Hydro-Québec and the Inuit formally began in 1990, this working group was made part of the team designated for dealing with the proponent and participating in the environmental assessment process, in consultation with the people from the directly affected communities and the Nunavik population in general. This team was made up of lawyers, an array of consultants, three Makivik representatives, as well as six full-time and 12 part-time representatives from the three most directly impacted communities (see Fig. 3).

In conjunction with the other members of the team, the Inuit representatives undertook: (1) to make presentations at public hearings held in the communities; (2) to respond to the consultation document distributed by Hydro-Québec in each community; and (3) to submit the EIS to the appropriate level of scrutiny required in the context of the environmental and negotiation processes.

Also, as mentioned earlier, Makivik tabled a 200 page report in which the EIS was analysed regarding its conformity with the Guidelines. Preparation of this document required contributions by some 20 experts and the involvement of the 18 Inuit members; comments and recommendations from technical consultants were incorporated in the input from the Inuit task groups. The resulting draft report was reviewed several times and the final document was tabled with the evaluating committees.

As consultations and discussions were taking place, representatives from the Inuit communities were apprising people of the developments and recording any feedback, primarily through community radio stations, which soon became the medium of choice for reaching the members of the community. As a matter of fact, all Inuit were listening in at certain times during the day and thus were able to phone in their comments directly. Through this procedure the community representatives were able to bring back to the team the public consensus as it was built up.

This inflow of ideas was not limited to the three most affected communities, since the Makivik Corporation kept the general Nunavik population abreast of ongoing negotiations and the progress made in the environmental assessment process. Finally, in February 1994, at a meeting held in Montreal, more than 70 representatives from all Nunavik communities ratified the previously mentioned Kuujjuarapik Agreement-in-Principle that was the result of months of negotiations.

Thus a consensus was achieved through the iterative process; the affected communities as well as the general Nunavik population were an integral part of the decision making process.

7. CONCLUSIONS

In the context of the parallel direct negotiations and concurrent environmental assessment processes, the Grande-Baleine project was reviewed, discussed, analysed and changed. In drafting the Guidelines, the review committees bore in mind the wishes and concerns voiced by the most affected people. The Inuit participation in these decision making processes was based on an interactive dialogue between the Makivik Corporation and the members of the communities.

Step by step, a consensus emerged, as each and every project component was scrutinized. The Agreement-in-Principle was signed only after a time consuming discussion that involved representatives from every part of Nunavik.

The principles embodied in the World Bank policy on public consultation and participation [2] were more than strictly adhered to, as the Inuit were not only involved in the environmental assessment process but were also able to enter into negotiations with the proponent of the project.

The methodology developed was not subjected to scientific analysis or validation. Nevertheless, the expected results were achieved in terms of consultation and participation. Moreover, the community members gained a measure of confidence in and control over the events which they would not have had otherwise — they felt clearly that they were active players, not merely passive spectators.

Yet, some concerns remain unaddressed. Although the Premier of Quebec in November 1994 postponed the Grande-Baleine project indefinitely, the mobilization of the population within the communities of Nunavik will not be forgotten soon. One can hardly expect that these communities will emerge unscathed from the experience they went through and that these events will have no social impact. The people in these communities are trying right now to identify and explain the disquiet they feel deeply. Because of this, Hydro-Québec was requested to investigate the social impacts from the project that was never realized.

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ASSESSMENT OF HEALTH AND ENVIRONMENTAL IMPACTS

(Session 2)

Chairman

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ISSUES OF DATA COLLECTION AND USE FOR QUANTIFYING THE IMPACTS OF ENERGY INSTALLATIONS AND SYSTEMS

B. SØRENSEN
Institute of Studies in Mathematics and Physics,
Roskilde University,
Roskilde, Denmark

Abstract

ISSUES OF DATA COLLECTION AND USE FOR QUANTIFYING THE IMPACTS OF ENERGY INSTALLATIONS AND SYSTEMS.

The paper discusses several critical issues in the construction of models for assessing the impacts of energy installations and systems. Some of these are connected with the process of data collection and use; it is pointed out that different methods have to be applied according to the purpose envisaged for a particular study (e.g. plant licensing, environmental assessment or energy planning). Further concerns are discussed, related to the common need to aggregate data and, in relation to the actual client or target group of the work, to present results in a sufficiently generic fashion. The paper discusses aggregation over technologies, over sites, over time and over social settings. Regarding the actual technique used for impact calculations, the differences between externality calculations, extended risk analysis and life cycle analysis are described. Finally, the issue of quantification is illustrated by two very difficult but also very important examples: global climate impacts and impacts of nuclear accidents.

1. DATA ACQUISITION

Impact assessment requires the collection of primary data on the physical interplay between a given energy installation or system and its environment. These data include emissions and other releases, noise levels, etc. The pathway approach employed for site and technology specific studies, as well as generic data appropriate for other types of investigation are discussed.

1.1. Pathway method

For an energy installation (power plant, mine, refinery, a piece of end use equipment, etc.) at a given location, an impact analysis for the particular step in the energy conversion chain represented by the installation can be made according to the pathway method, as illustrated in Fig. 1. In principle, this method applies both to normal operation of the installation and to accident situations.

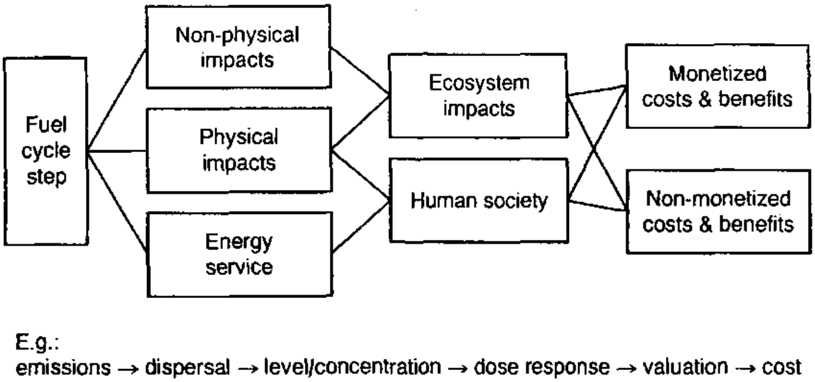

FIG. 1. Pathways for evaluating impacts [7].

The initiating step may be to calculate impacts in the form of emissions (e.g. of chemical or radioactive substances) from the installation to the atmosphere, releases of similar substances to other environmental reservoirs, or emissions of noise. Other impacts could be from inputs into the fuel cycle (water, energy, materials such as chalk for scrubbers). In a life cycle analysis, the indirect impacts associated with the production of these inputs (typically at other sites, using other equipment) have to be enumerated, as well as the inputs to inputs, for as long as significant impacts are involved. Basic emission data are being routinely collected for power plants, whereas data for other conversion steps are often more difficult to obtain. Of course, emission data, e.g. from road vehicles, are available in some form, but they are rarely distributed over driving modes and location, as one would need in most assessment work.

The next step is to calculate the dispersal of releases in the ecosphere, for example by using available atmospheric or aquatic dispersion models. In the case of radioactivity, decay and transformation also have to be considered. For airborne pollutants, the concentration in the atmosphere is used to calculate deposition (using models for dry deposition, deposition by precipitation scavenging or deposition after adsorption or absorption of pollutants by water droplets). From this, the distribution of pollutants (possibly transformed from their original form, e.g. sulphur dioxide to sulphate aerosols) in the air and on the ground or in water bodies will be obtained, normally given as a function of time, because further physical processes may move the pollutants down through the soil (where they would eventually reach the groundwater or aquifers) or again into the atmosphere (e.g. as dust).

If the concentration of pollutants is given as a function of place and time, the pathway may be further expanded to include an impact on humans, such as by ingestion of the pollutant. Rather large areas may have to be considered, both for normal releases from fossil fuel power plants and for nuclear plant accidents (typically for a distance from the energy installation of 1000 km or more). Besides the negative impacts, there are of course positive impacts derived from the energy produced. These impacts will have to be weighed against each other. In some cases, the comparison is assisted by translating the dose responses (primarily given as number of cancers, deaths, workdays lost, and so on) into monetary values. This should only be done if the additional uncertainty introduced by monetizing is not so large that the evaluation of the monetized impacts becomes arbitrary. In any case, some impacts are likely to remain which cannot meaningfully be expressed in monetary terms.

1.2. Generic data

If the purpose of the assessment is to obtain generic energy technology evaluations (e.g. as inputs into planning and policy debates), one would try to avoid using data that depend too strongly on the specific site selected for the installation. These could be important impacts, depending on a specific location (involving, for example, special dispersal features, such as in a mountainous terrain) or a specific population distribution (presence of high density settlements near the energy installation studied). In policy discussions, these special situations should normally be avoided, whereas, in the case of actual site selection, unsuitable locations can be avoided if the planning area is sufficiently diverse.

Pure emission data are often dependent only on the physical characteristics of a given facility (power plant stack height, quality of electrostatic filters, sulphate scrubbers, nitrogen oxide treatment facilities, and so on), and not on the site. However, the dispersion models are of course site dependent, but general concentration versus distance relations can usually be derived in model calculations avoiding any special features of sites. As regards the dose commitment, it will necessarily depend on the population distribution, while the dose response relationship should not depend on this. As a result, a generic assessment can in many cases be performed, with only a few adjustable parameters left in the calculation, such as the population density distribution, which may be replaced by average densities for an extended region.

The approach outlined above will only serve as a template for assessing new energy systems, as the technology must be specified and usually would involve a comparison between state of the art, new technologies. If the impacts of the existing energy system in a given nation or region have to be evaluated, the diversity of the technologies in place must be included in the analysis, which would most likely have to proceed as a site and technology specific analysis for each piece of equipment.

In generic assessments, it is not only necessary to fix the technology and population distribution but also to assume a number of features of the surrounding society, inasmuch as they may influence the valuation of the calculated impacts (and in some cases also the physical evaluation, e.g. as regards the preparedness of society to handle major accidents, which may influence the impact assessment in essential ways).

2. AGGREGATION ISSUES

Because of the importance of aggregation issues, both for data definition and for calculation of impacts, this topic will be dealt with in some detail. There are at least four dimensions of aggregation that play a role in impact assessments:

— Aggregation over technologies,
— Aggregation over sites,
— Aggregation over time,
— Aggregation over social settings.

The most disaggregated studies done today are termed 'bottom-up' studies of a specific technology located at a specific site. Since the impacts will continue over the lifetime of the installation and possibly longer (radioactive contamination), there is certainly an aggregation over time involved in stating the impacts in compact form. The better studies attempt to display impacts as a function of time, e.g. as short, medium and long term effects. However, even this approach may not catch important concerns, as it will typically aggregate over social settings, assuming them to be inert as a function of time. This is of course never the case in reality and, in recent centuries, the development of societies with time has been very rapid, entailing also rapid changes in social perceptions of a given impact. For example, the importance presently accorded to environmental damage was absent just a few decades ago, and there are bound to be issues about which society will be concerned over the next decades, but which currently are just considered as marginal by wide sections of society.

The item of aggregation over social settings also has a precise meaning at a given instance. For example, the impacts of a nuclear accident will greatly depend upon the response of the society. Will there be heroic firemen, as in Chernobyl, who will sacrifice their own lives in order to diminish the consequences of the accident? Was the population properly informed about what to do in the case of an accident (going indoors, closing and opening windows at appropriate times, etc.)? Were there drills of evacuation procedures? The answers to these questions are "no" for Russia and "yes" for Sweden. A study making assumptions on accident mitigation effects must be in accordance with the make-up of the society for which the analysis is being performed.

Aggregation over sites implies that peculiarities in topography (leading perhaps to irregular dispersal of airborne pollutants) are not considered and that variations in population density around the energy installation studied will be disregarded. This may be a sensible approach in the planning phase, where the actual location of the installation may not have been selected. It also gives more weight to the technologies themselves, making this approach suitable for generic planning choices between classes of technology (e.g. nuclear, fossil, renewable). Of course, once actual installations are to be built, new, site specific analyses may be invoked in order to determine the best location.

Aggregation over technologies would in most cases not make sense. However, in the particular case of assessing the existing stock of, for example, power plants in a region, something like technology aggregation may play a role. For example, one might use average technology for the impact analysis, rather than performing multiple calculations for specific installations involving both the most advanced technology and the most outdated technology.

In a strict sense, aggregation is never allowed, because the impacts that play a role never depend linearly or in simple ways on assumptions of technology, topography, population distribution, and so on. One should in principle treat all installations individually and make the desired averages on the basis of the actual data. This may sound obvious, but it is also unachievable because only for some issues can the actual situations underlying the averages be addressed. As regards the preferences and concerns of future societies, or the future impacts of current releases (such as climate impacts), one will always have to do some indirect analysis, involving aggregation and assumptions on future societies (using, for example, the scenario method).

It can be concluded that some aggregation is always required, but that the level of aggregation must depend on the purpose of the assessment. The following purposes for impact assessments currently performed can be discerned:

— Licensing of particular installations,
— Energy system assessment,
— Energy planning and policy.

For licensing of a particular installation along a fuel chain or for a renewable energy system, clearly a site and technology specific analysis has to be performed, making use of actual data for physical pathways and populations at risk (as well as corresponding data for impacts on ecosystems, etc.). For the assessment of a particular energy system, the full chain — mining or extraction, refining, further treatment, transportation to and use in power plants, followed by transmission and final use — must be considered, and each step would typically involve different locations. A complication in this respect is that, e.g. for a fuel based system, it is highly probable that, over the lifetime of the installation, fuel would be purchased from different vendors, and the fuel would often come from many geographical areas with widely differing extraction methods and impacts (e.g. Middle East versus North Sea oil or gas, German or Bolivian coal mines, open pit coal extraction in Australia, and so on). Future prices and environmental regulations will determine the change in fuel mix over the lifetime of the installation, and any specific assumptions may turn out to be invalid.

For the planning type of assessment, it would be normal in most industrialized nations to consider only state of the art technology, although even in some advanced countries there is a reluctance to apply the available environmental cleaning options (currently for particle, SO_2 and NO_x emissions; in the future probably also for CO_2 sequestering or other removal of greenhouse gases). In developing countries, there is a tendency to ignore available but costly options of environmental impact mitigation. In some cases, the level of sophistication selected for a given technology depends on the intended site (e.g. near to or away from population centres). Another issue is maintenance policies. The lifetime of a given installation depends sensitively on the willingness to spend money on maintenance, and the level of spending opted for is a matter to be considered in the planning decisions.

Some of the issues involved [1] are listed below:

Technology and organization

— Type and scale of technology;
— Age of technology;
— Maintenance state and policy;
— Matching technology with the level of skills available;
— Management and control setup.

Natural setting

— Topography, vegetation, location of waterways, groundwater tables, etc.;
— Climatic regime: temperature, solar radiation, wind conditions, currents (if applicable), cloud cover, precipitation patterns, air stability, atmospheric particle content.

Social setting

— Scale and diversity of society;
— Development stage and goals;
— Types of Government, institutions and infrastructure.

Human setting

— Values and attitudes, goals of individuals;
— Level of participation, level of decentralization of decision making.

Impact assessments suitable for addressing these issues involve the construction of scenarios for future societies, in order to have a reference frame for discussion of social impacts. Because the scenario method is normative, it would in most cases be best to consider more than one scenario, covering important positions in the social debate of the society in question.

Another issue is the emergence of new technologies that may play a role over the planning period considered. Most scenarios for future societies do involve some assumption of new technologies coming into place, according to current research and development. However, the actual development is likely to involve new technologies that were not anticipated at the time of making the assessment. It is possible to analyse scenarios for sensitivity to such new technologies and sensitivity to possible errors in other scenario assumptions. This makes it possible to distinguish between those future scenarios which are resilient, i.e. those which do not become totally invalidated by changes in assumptions, and those which depend strongly on the assumptions made. In the case of energy technologies, it is equally important to consider the uncertainty of demand assumptions and assumptions on supply technologies. The demand may vary according to social preferences and according to the emergence of new end use technologies that may provide better services with less energy input. It is therefore essential to consider the entire energy chain, not just to the energy delivered, but all the way to the service derived. No one demands energy, but people demand transportation, air conditioning, computing, entertainment, and so on.

The discussion of aggregation issues clearly points to the dilemma of impact analyses: Those answers that would be most useful in the political context are often answers that can be given only with large uncertainty. This places the final responsibility in the hands of the political decision maker, who has to weigh the impacts associated with different solutions and in that process to take into account uncertainties (e.g. choosing a more expensive solution because it has less uncertainty). But this is of course what decision making is about!

3. DEPTH OF ANALYSIS

Any actual impact assessment involves the selection of a number of items that are considered important and the neglect of others, hopefully after reflections that make it probable that they will not change the overall results. In any case, there will be impacts that are not taken into consideration, e.g. because of new scientific insights that will only be obtained at a later stage, so any assessment has to live with the fact of incompleteness. On the methodological level, some cut-offs are systematically used in current assessment. These will be discussed in this section.

3.1. Life cycle analysis

Life cycle analysis (LCA) is a method by which it is possible in principle to assess both direct and indirect impacts of a technology, a product, a system or an entire sector of society. LCA incorporates impacts over time, including impacts deriving from materials or facilities used to manufacture tools and equipment for the process under study; LCA also includes final disposal of equipment and materials, whether involving reuse, recycling or waste disposal. The types of impact that may be contemplated for assessment reflect to some extent the issues that, at a given moment in time, have been identified as important in a given society. It is therefore possible that the list will be modified with time and that some societies will add new concerns to the list. The following impacts are listed in Ref. [1]:

- Economic impacts, such as impacts on owners' economy and on national economy, including questions of balance of foreign payments and of employment.
- Environmental impacts, e.g. land use, noise, visual impact, local pollution of soil, water, air and biota, regional and global pollution, and other impacts on the Earth atmosphere system, such as climatic change.
- Social impacts, related to satisfaction of needs, impacts on health and the work environment, exposure to risks, impact of large accidents.
- Security impacts, including both security of supply and safety against misuse and terror action.
- Resilience, i.e. sensitivity to system failures, planning uncertainties and future changes in criteria for impact assessment.
- Development impacts, e.g. consistency of a product or a technology with the goals of a given society.
- Political impacts, e.g. impacts of control requirements, and impacts on openness to decentralization in both physical and decision making terms.

There is a geopolitical dimension to the above issues: Development or political goals calling for import of fuels for energy may imply increased competition for scarce resources — an impact which may be evaluated in terms of increasing cost expectations or in terms of increasing political unrest (more 'energy wars'). The political issue also has a local component, pertaining to the freedom or lack of freedom of local societies to choose their own solutions, which may be different from the one selected by the people in neighbouring local areas.

3.2. Risk analysis

Risk analysis is normally defined by terms that are borrowed from the insurance industry, stating that "some sudden event outside the control of the insured operator" must be involved. However, some recent studies try to extend the definition to include all impacts that are of a stochastic nature [2, 3]. This would include impacts from normal operation of power plants because of the stochastic nature of some of the impact pathway processes. In the present paper, the conventional strict definition of risk will be used. This leaves mainly the accidents inherent in many technology solutions in the energy field (nuclear power stations, gas tankers and stores, oil pipelines, etc.).

It is necessary to make a few comments on the probabilistic treatment of accident risks. The standard risk assessment used in, for example, the airplane industry consists in applying fault tree analysis or event tree analysis to trace accident probabilities forward from initiating events or backward from final outcomes. The idea is that each step in the evaluation concerns a known failure type associated with a concrete piece of equipment and that the probability for failure of such a component should be known from experience. The combined probability is thus the sum of the products of partial event probabilities for each step along a series of identified pathways. It is important to realize that the purpose of this evaluation is to improve design, by pointing out the areas where improved design is likely to pay off. Necessarily, unanticipated event chains cannot be included. In areas such as airplane safety, it is clear that the total accident probability consists of one part made up by anticipated event trees and one part made up by unanticipated events. The purpose of the design efforts is clearly to make the probability of accidents that can be predicted by the fault tree analysis (and thus may be said to constitute 'built-in' weaknesses of design) small compared with the probability of unanticipated accidents, for which no defence is possible; in this case the only chance is to learn from actual experience and hopefully to move event chains including, for example, common mode failures from the 'unanticipated' category to the 'anticipated' category for which engineering design efforts may be addressed. This procedure has led to declining airplane accident rates, while the ratio between unanticipated and anticipated events has remained at approximately the value ten.

It should of course be said that the term 'probability' is used here in a loose manner, as there is no proof of a common, underlying statistical distribution [4] because of constant technological change, making the empirical data different from the outcome of a large number of identical experiments. This is equally true for cases of oil spills or nuclear accidents, for which there are few empirical data because of the low frequency of catastrophic events (albeit they are compounded by potentially large consequences). Here the term 'probability' is really out of place and, if it is used, it should be construed to mean just "an indicator of a possible frequency of events".

3.3. Externalities

The externality concept assumes that it is possible to distinguish between impacts that are included in the price of a product (here energy) and impacts that are not included. In other words, if there were no market imperfections, there would be no externalities. On the other hand, it is recognized that the broad range of possible impacts, including environmental and social impacts such as those listed in Section 3.1, have to be considered and, because some of them will remain qualitative or difficult to quantify, there will always be impacts that are not reflected in prices.

Of course, the players in the market place often try to pass on certain costs to society, betting on the current mixed economies to take care of less tangible impacts. Hardin [5] says that, for this reason, 'externalities' should rather have been termed 'impositions', as they are imposed upon society by those that should have included them in their cost structure.

Recently, efforts were made to get externalities back into the cost calculations (at least for planning and decision processes, if not for actual pricing, cf. the 'adders' used in US planning but never imposed on the prices). The use of common units for as many impacts as possible is of course in itself a noble aim, directed at facilitating the job of a decision maker wanting to make a comparison between different systems. Once monetized values are quantified, their introduction will be helpful in any comparison of different systems or facilities. However, it is important that this procedure does not further marginalize those impacts which cannot be quantified or which seem to resist monetizing efforts. The basic question is really whether or not the further uncertainty introduced by monetizing offsets the value of being able to use common units.

Monetizing may be accomplished by expressing damage in monetary terms or by using instead the cost of reducing the emissions to some low threshold value (avoidance cost). Damage costs may be obtained from health impacts by counting hospitalization and workday salaries lost, the cost of replanting dead forests, restauration of historic buildings damaged by acid rain, and so on. The cost of accidental death may be replaced e.g. by the insurance cost of a human life. Unavailability of data on monetizing has led to the alternative philosophy of interviewing sections of the affected population on the amount of money they would be willing to pay to avoid a specific impact or to monitor their actual investments (contingency evaluations such as hedonic pricing, revealed preferences, or willingness to pay). The outcome of such measures may change from day to day, depending on the exposure of people to random bits of information (whether true or false); it also depends strongly on the disposable income of people, as well as on competing expenses of a perhaps more tangible nature. The question is whether the statistical value of life (SVL) should be reduced by the fraction of people actually taking out life insurance, or whether it should be allowed to take different values in societies of different affluence.

All of the above methods are clearly deficient: the use of a damage cost because it does not include a (political) weighing of different issues (e.g. weighing immediate impacts against impacts occurring in the future), and contingency evaluation because it includes such a weighing on a wrong basis (influenced by people's knowledge of the issues, by their accessible assets, etc.). The best alternative may be to present the entire impact profile to decision makers, in the original units and with a time sequence indicating when each impact is believed to occur, and then to invite a true political debate on the proper weighing of the different issues.

A special role is played by problems of intergenerational equity — an issue that becomes relevant for many impacts from energy systems because of delays between cause and effect, particularly in the case of nuclear energy. Several studies of monetized impacts use a discount rate to express the preference of having assets now rather than in the future. This preference is evident for individuals with a finite lifespan; but, regarding national economies, the question arises whether assets that are left to future generations might not be exploited by them in a better way than is possible with present technologies. The same may be true for liabilities, such as nuclear waste, which can be stored for later processing, whereas for air pollution the impacts are of course already committed at the time of ingestion. Most people would prefer a cancer occurring 20 years later to one occurring now, but the question becomes more subtle if continuous suffering is involved. The intergenerational interest rate should basically be zero, placing the same value on the future as on the present. However, some would argue that we build up a stock of amenities for the future, which, together with the technological progress that will enable cheaper handling of deferred problems, would point to a positive discount rate. On the other hand, knowledge regarding health and environmental impacts is likely to grow with time, making, for example, environmental standards likely to become more stringent in the future (continuing their development over the last couple of decades). Also, new concerns are likely to emerge, all of which points to a negative discount rate. Because there is no way of telling precisely what future societies will be concerned with, the most reasonable choice of an intergenerational discount rate in my view is zero.

4. TWO EXAMPLES

The two examples treated below are characterized by having very large uncertainties; at the same time, they are essential to the assessment of fossil and nuclear energy systems. In monetized evaluations, these single impacts are likely to overshadow other impacts from the same technologies by one or two orders of magnitude.

4.1. Global climatic effects

The impacts of greenhouse gas emissions, leading to global warming and to possible impacts of a changed climate with greater variability, are estimated in Table I on the basis of assessment work performed by Working Group II of the Intergovernmental Panel on Climate Change (IPCC) [8]. The assumption of monetizing deaths using an SVL amounting to 2.6 MECU is used in all cases. If the value of life and health in developing countries were taken as zero, the global warming impacts estimated in Table I would diminish by a factor of 40.

The impacts estimated in Table I are for the IPCC reference scenario, which assumes a doubling of the greenhouse gases in the atmosphere by the middle of the

TABLE I. ESTIMATED IMPACTS OF GLOBAL WARMING DURING THE 21st CENTURY FOR THE IPCC REFERENCE CASE[a]

	Valuation (TECU)
Additional heatwave deaths (1 million, valued at 2.5 MECU each)	2.5
Fires due to additional dry spells	1.0
Loss of hardwood and fuelwood producing forests	3.0
Increase in skin cancer due to UV radiation	2.5
Additional asthma and allergy cases	2.0
Financial impact of increase in extreme events	2.0
Additional crop pests and adaptation problems for new crops	2.0
Increase in insect attacks on livestock and humans.	1.0
Increased death from starvation due to crop loss (100 million deaths, the affected population being over 300 million)	250.0
Deaths connected with migration caused by additional droughts or floods (100 million deaths, the affected population being over 300 million)	250.0
Increased mortality and morbidity due to malaria, schistosomiases, cholera, etc. (100 million deaths, the affected population being over 1000 million)	250.0
Other effects of sanitation and freshwater problems connected with droughts, floods and migration	25.0
Total of valuated impacts	791.0

[a] Based on discussions in Ref. [8]; valuation estimates were made separately; the uncertainty is very high.

21st century, as compared with the pre-industrial level. However, the impacts themselves are accumulated over the 21st century, since many of them occur over a period of time. Power production using fossil fuels currently amounts to some 7000 TW·h/a and is responsible for about 20% of greenhouse gas emissions. Thus the electric power generation share of impacts may be taken as 150 TECU. It is more difficult to express this per kilowatt-hour, but, if one assumes that the impacts are the result of 50 years of producing on average 10 500 TW·h/a (consistent with a doubling in 50 years), one obtains 0.3 ECU/kW·h. This is the estimate that should be used in assessments of fossil power (but acknowledging the large uncertainty involved).

TABLE II. FREQUENCY OF AND DAMAGE FROM LARGE NUCLEAR ACCIDENTS

Accumulated experience at the time of the Three Mile Island accident (1979)	3 000 TW·h
Accumulated experience at the time of the Chernobyl accident (1986)	5 800 TW·h
Accumulated experience up to the end of 1994	20 000 TW·h
Implied order of magnitude for frequency of core melt accident	1×10^{-4} (TW·h)$^{-1}$
*Implied order of magnitude for an accident with Chernobyl type releases	5×10^{-5} (TW·h)$^{-1}$
Chernobyl:	
Dose commitment [9]	560 000 man·Sv
Induced cancers (SVL = 2.6 MECU, no discounting)	200 GECU
Birth defects	20 GECU
Emergency teams, cleanup teams, security teams	50 MECU
Early radiation deaths (SVL = 2.6 MECU)	100 MECU
Evacuation and relocation	100 MECU
Food bans and restrictions	100 MECU
Unplanned power purchases	1 GECU
Capacity loss and reduced supply security	10 GECU
Cost of encapsulation and cleanup (at plant and elsewhere)	170 GECU
Increased decommissioning costs	100 GECU
Impact on the nuclear industry (reputation, reduced new orders)	100 GECU
Time spent by experts and regulators for monitoring	10 MECU
Concerns of the general public (psychosomatic impacts)	100 MECU
Total estimate of Chernobyl accident costs	600 GECU
Industry average accident cost using the above estimate marked by an asterisk	30 mECU/kW·h

1 mECU = US cents 0.125.

4.2. Nuclear accidents

The observed number of large accidents is for two nuclear core melt accidents (Three Mile Island and Chernobyl); for large oil spills the number of accidents is similar or smaller. The implied 'probability' in the nuclear case is illustrated in Table II. Counting two accidents over the accumulated power production to the end of 1994, one obtains a frequency of 10^{-4} per TW·h, or a frequency of 5×10^{-5} per TW·h for an accident with severe external consequences. At the time of the Chernobyl accident, the estimate would have been three to four times higher because of the much lower accumulated power production of reactors worldwide by 1986. For comparison, the built-in probability for an accident with Chernobyl type consequences for a new, state of the art light water nuclear reactor was calculated by the fault-tree analysis to be of the order of 10^{-6} per TW·h [6]. The difference between the two numbers comes partly from the difference between a state of the art reactor and the average reactors in operation, and partly from the difference between the calculated probability of anticipated accidents and the actual frequency, including unanticipated events. Including unanticipated events may raise the estimate by about a factor of ten (as mentioned in Section 3.2), according to sound engineering practices, and the factor for average to state of the art reactors would be about four. Thus, the relation of numerical estimates of the calculated and observed accident rates can be generally understood.

Of the 0.3 ECU/kW·h attributed to accidents, one third represents the health impacts from radioactive releases, while two thirds are due to handling the accident (evacuation, food ban, cleanup, backup power, etc.) and to indirect costs. The use of empirical data for analysis of large accidents at power plants may be criticized because of the fact that technological progress was not taken into account (see the above discussion on average and state of the art technology). However, the present expansion of nuclear power takes place in developing countries, so it would seem prudent not to count on the higher standards of operational safety achieved in industrialized countries over the last decade. For example, reduction of impacts through early warnings, indoor confinement of people, with controlled closure and opening of windows, evacuation and food bans is much less likely to function in developing countries. In fact, early recognition of and public information on a problem, which are essential for certain accident types, did not characterize the historic examples of accidents.

5. DISCUSSION

Many studies make the assumption that the new systems considered are marginal additions to the existing system. This implies that in calculating the impacts of manufacturing, for example, photovoltaic panels, the energy input comes from the current mix of power plants, typically coal fired plants or nuclear ones. Evidently, this gives results that are very different from those which would emerge from a study assuming a transition to an energy supply system based on renewable energy sources, where the manufacturing impacts would come from solar, wind and biomass plants. An alternative would be to construct a scenario for an energy transition, and then use the scenario mix of energy sources for calculating impacts at a given time. This type of investigation is currently under study, and improved data are expected to be derived from such analyses.

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RENEWABLE ENERGY TECHNOLOGIES AND THEIR ADAPTATION TO RURAL ECONOMIC DEVELOPMENT IN CHINA

Junfeng LI, Lin DAI, Litong XU
Energy Research Institute,
State Planning Commission,
Beijing, China

Abstract

RENEWABLE ENERGY TECHNOLOGIES AND THEIR ADAPTATION TO RURAL ECONOMIC DEVELOPMENT IN CHINA.

Renewable energy technologies have been developed in China during and after the 1980s, in connection with the rural economic development. The paper presents the development status of renewable energy technologies and their adaptation to the rural economic development in China. A detailed cost/benefit analysis for renewable energy technologies is given. The environmental impacts of these technologies are also discussed.

1. BACKGROUND

Nearly one fifth of the world population lives in the rural areas of China. In most of these areas, energy supplies are scarce, which leads to over-exploitation of the existing forestry and farm lands. This in turn causes severe environmental damage. Before 1980, Chinese peasants depended almost entirely on biomass resources as domestic fuels. Coal and other fossil fuels were mainly used in urban areas. Most of the renewable low cost energy resources are for non-commercial use. For example, about 70% of the 224 million tce of biomass is used non-commercially, and less than 10%, mainly firewood and charcoal, is sold on the market. In other words, the main aim of the Chinese development programme for renewable energy is to provide energy to the rural population. Following the reform of the economic system in China and the open door policy, the living conditions of the rural population and the rural economy have been improved. As a result, commercial use of energy resources, including coal and other fossil fuels, is playing a significant role in the rural areas.

About 80% of the total population of China lives in rural areas, and rural economic development plays a very significant role in the national economic development, particularly following the rural industrial development. As a result, the energy demand and supply in connection with rural economic development have become very important issues in the Chinese energy supply strategy. Because of the large amount of resources available, renewable energy resources have played a very large role in rural energy supply. By the end of 1993, about 250 million tce of biomass were used by rural households and for rural economic development, which was about 20% of the total energy supply in China. Therefore, the development of renewable energy in China is being recognized as an important component of long term sustainable energy supply.

Given the commitment of the World Environment and Development Convention, greenhouse gas (GHG) reduction is an important issue for the international community. As one of the major measures of GHG reduction, the development of renewable energy technologies has been recommended as a high priority task in China. In 1993, the State Council of China instituted Agenda 21, a major component of which is the development of renewable energies. Since 1994, the State Planning Commission, the State Science and Technology Commission and the State Economic and Trade Commission have jointly formulated a programme for the development of new and renewable energies for the period 1996–2010. On the basis of this programme, the commissions are preparing an implementation schedule for the ninth five-year plan.

However, on the basis of the concept of a least-cost energy supply strategy, renewable energy development is intended mainly for rural households and for the development of rural economy. In 1994, China had about 80 million poor people and most of them lived in remote areas where fossil fuel resources are scarce and supply costs are high. Development of renewable energies is usually associated with the elimination of poverty; in other words, solving the problem of energy shortage is one of the major tasks necessary to achieve this aim.

2. RENEWABLE ENERGY RESOURCES AND TECHNOLOGIES

2.1. Wind energy

As estimated by the National Meteorological Bureau and the Meteorology Institute, the capacity of wind energy in China is about 1.6 TW, and the existing installed capacity of wind power generators is about 30 MW. The criteria for qualitative determination of the potential of wind energy are divided into high, moderate, marginal and poor (see Table I).

Most of the high potential wind energy generators are located in areas that are far away from industrialized regions. However, in most of these areas, other energy resources are scarce. Wind power generation could be used in remote rural areas, such as Inner Mongolia, and on islands in the eastern coastal regions.

China has a long history of wind turbine and wind power development, which started in the early 1950s with the development of small turbines for application in remote areas. By the end of 1994, there were about 140 000 household size wind turbines which supplied electricity to the population in remote rural areas, especially

TABLE I. CRITERIA FOR QUALITATIVE DETERMINATION OF THE POTENTIAL OF WIND ENERGY

Criteria	High	Moderate	Marginal	Poor
Hours/year with wind velocities of >3 m/s	>5000	4000–5000	2000–4000	<2000
Hours/year with wind velocities of >6 m/s	>2000	1500–2000	500–1500	<500
Wind energy density	>200	150–200	50–150	<50

TABLE II. COST COMPARISON OF WIND/DIESEL HYBRID SYSTEMS AND CONVENTIONAL DIESEL SYSTEMS (yuan/kW·h)

Cost elements	Hybrid system	Diesel system
Investment	0.33	0.14
Operation and maintenance	0.06	0.15
Fuel	0.40	0.75
Total	0.79	1.04

husbandry farmers of Inner Mongolia; the costs of these wind turbines were comparable with those of diesel generators.

In recent years, China has also developed some grid connected wind farms, which use mainly imported equipment and technologies. By the end of 1994, about 14 sites of wind farms had been set up, with a total capacity of about 30 MW. Currently, most of the grid connected wind farms are located in rural areas and supply electricity to the rural economy.

China has also developed technologies for so-called hybrid systems. A number of wind/diesel/battery systems in the range of 30–130 kW are being tested in China. These systems are mainly located in Inner Mongolia and on islands in the coastal region.

The most popular wind turbine in China is of a size suitable for households in remote rural areas. A typical small wind energy system consists of a

100 W generator and two batteries of 60 A·h each. This system is able to supply energy for two or three fluorescent lights, a black and white television set and a radio, depending on the wind resource and the battery charging capacity. In 1993, the total cost of the system was about 1060 yuan, and the levelized power generation cost was about 0.85 yuan per kilowatt-hour, which was lower than the cost of diesel power generation in some regions.

The cost of power generation by a hybrid system is lower than that by a conventional wind power system. Table II presents a cost comparison of hybrid and conventional diesel systems.

2.2. Solar energy

Solar energy is abundant in China, especially in the north-eastern parts and in Tibet and the Yunnan province. The solar radiation intensity is about 0.6 MJ per square metre. The most popular way of using solar energy is through heating panels that are applied mostly on the roofs of houses. Solar heating panels of an area of about 3.3 million m^2 have been installed previously in China, and about 0.8 million m^2 of such heating panels are produced annually. These solar heating panels can supply hot water to both rural and urban areas for residential use. Another utilization of solar energy is the provision of solar housing systems. By the end of 1994, housing systems with about 150 000 m^2 of heating panels had been provided. These houses were located mainly in the north-eastern and north-western parts of China. Both solar heating panels and solar housing systems mainly provide energy for the needs of households. However, some of these panels are used also in agriculture, e.g. for drying tea, tobacco and bricks. According to calculations by the Ministry of Agriculture (MOA), solar heating panels can provide about 1 million toe for energy production for rural and urban households.

In China, the solar photovoltaic (PV) technology is used mainly for solar power generation. The annual capacity of solar PV power production is about 3–5 MW_{peak}; most of it is sold to companies using signalling systems for communication and transportation; some of it is sold to to rural households. Because of the high cost of solar PV energy, it is hardly suitable for poor people in rural households. Currently, one W_{peak} of PV energy from a battery system costs about 100 yuan, i.e. a 50 W_{peak} system costs about 5000 yuan. The per capita income of most of the poor people in rural areas is less than 200 yuan per year. A household of five people would need the total income of five years to buy one solar PV system. Therefore, the development of solar PV systems in China is based mainly on three strategies: (1) PV energy is sold to relatively rich husbandry farmers who can pay the total cost of the system, with different payment options, e.g. high or low down-payment; (2) PV energy is sold to households with moderate incomes, with Government subsidies; and (3) PV energy is provided to poor people who do not have enough money to buy a solar PV system. The money for dissemination of solar PV energy comes mainly from the Government fund for the elimination of poverty, from bilateral or multilateral assistance funds and from international assistance funds.

Technologies for solar power generation connected to the grid and for solar thermal power generation have not been developed and utilized in China. However, it has been proposed to use these kinds of technology for overcoming power shortages in Tibet, since this option seems to be the cheapest one for that region.

2.3. Biomass energy

China has a wide range of biomass resources that can be used for energy generation; these resources include firewood, straw and stalks, agriculture and forestry residues and organic wastes. The annual production of biomass resources in China is shown in Table III. The annual biomass production is about 5000 million tonnes, of which about 600 million tonnes can be used for energy production.

TABLE III. BIOMASS ENERGY RESOURCES IN CHINA (1993)

Biomass resources	Annual production (million tonnes)
Crop straw	450
Forestry residue	15
Garbage	73
Municipal sewage	146
Rice husks	15
Sugar cane	67
Waste water	18 250

Biomass is the major energy resource that can be used as fuel for households. Biomass provides about 70% of the energy for households in rural areas; in some remote areas, biomass provides about 100% of the energy for households. In recent years, following the economic development in rural areas, people used commercial energy instead of energy from biomass. In 1993 the amount of coal used in rural areas was twice that in 1980 and reached about 100 million tonnes. However, because of increased environmental pressure, utilization of biomass energy has become an important issue in China. If rural households would rely too much on biomass energy, then the impact on forestry and land use would become more serious. On the other hand, the use of large amounts of coal in rural areas would cause more pollutants; the current environmental situation in China is already very serious, especially regarding emissions of total suspended particles and SO_2.

The strategy of biomass energy utilization in China can be described as follows: (1) increasing the efficiency of biomass energy, for example by promotion of the programme for providing improved stoves in rural areas; and (2) promoting the commercial utilization of biomass energy, such as biomass gasification (e.g. biogas). In the past 20 years, the programme for providing improved stoves was successful; by the end of 1994, more than 70% of rural households had improved stoves. However, commercialization of biomass energy is progressing very slowly because of high costs and decentralization problems.

Firewood is one of the major biomass resources for energy use in rural areas; it provides about 70% of the total biomass energy for households. However, firewood resources are scarce, since the land that can be used for firewood plantations is limited. Currently, most of the firewood (more than 70%) comes from timber and other forestry plantations, which results in a lower productivity of these plantations. By 1993, about 5.5 million hectares of firewood plantations supplied about 30 million tonnes of firewood. Thus, increasing the area of firewood plantations will be one of the options for supplying enough energy to the rural population, without negative impacts on both the local and the global environment.

Biogas production used to be one of the measures for commercial utilization of biomass resources. However, because of problems in connection with the maintenance of the equipment used, the speed of biogas development slowed down in the late 1980s compared with that in the 1970s. One target of the biogas development programme was the development of technologies that can be used in rural households by people to perform certain activities that will provide a source of income. For example, in the north-east of China, biogas digesters did not work well because of the cold weather in this part of the country. However, recently, farmers have combined solar greenhouse systems with biogas digesters. The solar greenhouse system supplies heat for both the house and the biogas digester, and the biogas supplies energy for the household. Biogas residues can be used as fertilizer for the vegetables grown in the greenhouse. Therefore, biogas plays a key role in activities aimed at combining energy supply, environmental protection and economic development of rural households. It has been calculated that for rural households the income from one greenhouse with a biogas digester can be increased by about 6000 yuan. Therefore, a biogas programme was developed for the north-east of China. In 1994, 10 000 biogas digesters were installed in the province of Liaoning alone. By the end of 1994, about 5.3 million households in rural areas used biogas digesters to produce biogas for cooking and lighting purposes.

Another target of the biogas programme is to develop large scale biogas digesters and to use them for supplying clean energy to rural and urban households; biogas could even be used for power generation for economic development of rural areas. One important component of the plan for the development of new and renewable energy sources is large scale development of biogas. The development of large scale biogas digesters depends upon the growth of the rural economy. In recent years, there was a very large increase in large scale animal husbandry farms to meet the meat demand of people in both rural and urban households. Since a large amount of animal residues accumulates in such farms, the biogas digester technology is used as a means of both energy production and environmental protection. In the rural areas of Beijing, ten husbandry farms have been selected to demonstrate biogas production and power generation in a pilot project in which both energy and power are supplied to the farms.

Biomass gasification and briquetting technologies are other options for the commercial utilization of biomass. In recent years, China has developed several biomass gasification and briquetting technologies. However, the cost of these technologies is high and their reliability is low. Thus, biomass gasification and briquetting technologies are still in the research and development stage and far from commercial utilization.

2.4. Geothermal energy

The total resources of geothermal energy in China represent about 3000 million tce, of which about 0.3 million tce have been utilized. Geothermal energy resources can be divided into two types: high temperature (>150°C) resources, which are located mainly in the Yunnan province–Tibet geothermal zone and in the eastern Taiwan geothermal zone; and low temperature resources. However, it is difficult to use high temperature resources for rural economic development. For rural areas, mainly the low temperature geothermal resources are utilized; these are located in the northern part of China (Hebei and Beijing areas). Geothermal energy is used mainly for heating of houses and greenhouses. The utilization potential of geothermal energy depends on the availability of resources and on the cost of drilling.

3. GOVERNMENT PROGRAMMES FOR DEVELOPMENT OF RENEWABLE ENERGY RESOURCES

3.1. Programme for development of improved stoves and biogas technology to solve problems in connection with energy shortage in rural areas

In China, the housewife is the person mainly responsible for cooking and firewood collection. In some rural areas, a housewife spends about 4–8 hours or 50–90% of her time for cooking and collection of firewood. The efficiency of stoves can be improved by about 10–15 percentage points, and about one third of the cooking time and 50% of the time spent for firewood collection can be saved. During the past 12 years, the Ministry of Agriculture has installed about 150 million efficient stoves in rural areas. This programme not only helps save energy but it also gives women more time for production and education activities. As a consequence of the improved stove programme, the economic activities of women in some rural areas have become an important source of income.

In China, biogas is not only used as fuel for cooking and lighting; its residual liquid and sludge can also be utilized and thus its economic return significantly improved.

In 1994, there were 5.3 million users of biogas digesters in rural areas and the average biogas generation was 273 m^3 per household; compared with 1993, the number of biogas digesters increased by 266 000. There were also over 600 large scale projects which used organic sewage from industries and agriculture; they supplied biogas to over 84 000 households in urban areas throughout the year; the average biogas supply to households was 438 m^3 annually. In addition, 12 800 facilities used biogas for storage of grain, with a capacity of 126 kt; this prevented the loss of 129 kt of grain. Seeds soaked in the slurry from biogas digesters were sown on agricultural land of an area of 268 000 ha; the increment in grain output was 130 kt.

Biogas technologies can be used to treat sewage from townships; in 1993, there were 24 800 biogas projects for sewage purification, which treated the domestic sewage from 2.5 million people.

3.2. Development programme for small hydropower resources for rural electrification

China has more hydropower resources than any other country, but only a fraction of these resources has been developed. More than 5000 rivers in China have catchment areas exceeding 100 km^2. The total hydropower potential in China was estimated at 676 GW. In addition, there are small hydropower resources with a potential of 70 GW, of which approximately 21% are currently being utilized. Compared with coal, which is abundant yet unevenly distributed, water resources are more equally distributed in China. For instance, more than 1000 counties in China have small hydropower resources. In the south-western region of the country, where coal is scarce, there are about 70% of the total hydropower resources.

Small hydropower facilities are power stations with a total capacity of less than 25 MW. Because of their small size, their development can be adapted to the small scale investment possibilities of rural areas. In the past ten years, the capacity of small hydropower facilities has been increased by about 1 GW per annum; 20% of the small hydropower resources has been exploited, whereas only less than 10% of the large hydropower resources has been exploited.

The use of small scale hydropower represents one of the major measures for rural electrification. In China, rural electrification is implemented mainly in three ways: (1) extension of the power network; (2) development of small scale hydropower facilities; and (3) installation of small scale fossil fuel (mainly coal and diesel) power generators. In the present situation, small scale hydropower contributes about 20% of the total rural electricity supply (see Table IV).

TABLE IV. POWER RESOURCES FOR RURAL ELECTRICITY SUPPLY

Electricity resources	Electricity supply (TW·h)	Percentage
Large power network	128.2	73
Small hydropower	31.6	18
Small thermal power	12.8	7.5
Small diesel power	2.6	1.5
Total	175.2	100

Because of the large contribution of small scale hydropower resources, the State Council, through the Ministry of Water Resources, instituted in 1983 a programme for rural electrification in 100 pilot counties located in regions that are inaccessible to the national power grid. The principal goals of the programme were: an installed capacity of 100 W per capita and an annual average electricity consumption of 200 kW·h per capita. By the end of 1989, 88% of the pilot counties had achieved these objectives. Between 1982 and 1989, the average net income per capita in the 100 pilot counties had increased from 200 to 500 yuan, with some counties reporting average per capita incomes as high as 1000 yuan. According to statistics from the 100 pilot counties, the total installed capacity reached 3040 MW, largely because of the increase in small hydropower installations.

3.3. Renewable energy development programme for elimination of poverty

There are about 80 million poor people in China, and about 100 million people have no electricity. Chinese ministries and commissions initiated several programmes for the development of renewable energy resources for power generation in connection with the programme for the elimination of poverty.

As one example, the State Planning Commission instituted a solar power generation programme together with the Ministry of Power. The aim of this programme was to use solar and wind energy for power generation in order to supply electricity to rural households in the north-western part of China and in other suitable areas. This programme was supported by bilateral and multilateral agreements. Solar power supply systems were set up in Tibet, Gansu, Qinghai and other areas, and wind power generators were installed in Inner Mongolia and in the eastern coastal region.

The Ministry of Water Resources launched a so-called 'warming spring' programme to promote the utilization of mini hydropower systems for direct supply of electricity to rural households or small businesses. The capacity of mini hydropower systems is less than 100 kW, with an average of several kilowatts; these systems supply electricity to households or small communities. Because of their low cost, mini hydropower systems are well accepted by the rural population. In most areas, the cost of electricity from mini hydropower installations is about 3000 to 4000 yuan per kilowatt, which is cheaper than that from small and large scale hydropower installations. The other advantage of mini hydropower systems is that no transmission network is required, which is usually the most expensive part of power systems.

The provision of solar housing systems for schools in northern parts of China (especially at 39–45° northern latitude) is the target of another important programme for the development of renewable energy carried out by the State Education Committee and the Ministry of Agriculture. In most of the northern parts of China, heating of houses is required during winter. However, in poor areas, primary schools usually have no heating systems. By providing solar housing systems for schools, the temperature inside the houses could be raised by about 10°C. Rural households in this part of the country could also benefit from this programme.

3.4. Integrated energy development programme for rural economies

In the early 1980s, an Integrated Rural Energy Development Programme (IREDP) was initiated by the Ministry of Agriculture, the Ministry of Forestry and the Ministry of Water Resources. The principles of IREDP are as follows: (1) provision of base energy supply under local conditions; (2) use of different energy resources that complement each other; (3) promotion of integrated utilization of energy resources; and (4) efficient use of energy and other resources. The main goal was to develop a least-cost energy supply programme for economic development and improvement of the living conditions in rural areas; this programme should mainly be based on local resources, i.e. new and renewable energy resources and technologies. In the early 1980s, three counties, located in south, central and north China, were selected to perform pilot demonstrations of IREDP. By the end of the 1980s, following the successful completion of these demonstrations, another

12 counties, representative of the various regions, were chosen for a large scale pilot demonstration of IREDP, which was instituted as the key project of scientific research during the seventh five-year plan. In the pilot phase, the rural counties benefitted from the least-cost energy supply programme, especially from the utilization of renewable energy resources and technologies. In comparison with other counties, the economic growth of these counties was fast. Since the benefit of IREDP had been verified, in the next period (that of the eighth five-year plan) the State Council instituted a large scale demonstration programme for integrated energy development — the so-called 100 counties programme. According to the evaluation of the results of this programme after five years, the 100 counties programme had been successful in the development of renewable energies suitable for adaptation to the rural economy. As calculated by the MOA, the potential energy supply from biomass had been increased to about ten million tce, through firewood plantations and utilization of solar heating panels and solar thermal power generation. About 40 million tce of energy could be saved by the provision of improved stoves and by other energy conservation and energy efficiency measures after demonstration of the programme in about 140 counties. Recently, the State Council approved a programme for another 100 counties for integrated rural economic development. A large amount of experience with renewable technologies and resource utilization for rural economic development has been acquired.

4. COST/BENEFIT ANALYSIS FOR RENEWABLE ENERGY TECHNOLOGIES

The major constraint to the development of renewable energy technologies is the fact that renewable energy resources are not competitive economically with commercially produced energy. However, in the long term, renewables are the cleanest and environmentally soundest energy resources. The utilization potential of renewable energy technologies cannot be realized without continuous research and development. The current demonstration of renewable energy technologies is a preparatory step for their further large scale use, and the evaluation of current technologies should consider their future development. On the other hand, the future large scale use of renewable energy technologies in rural areas depends on the marketing cost.

Even in the present situation, for example in remote rural areas where commercial energy is very expensive, renewable energy technologies can compete with other technologies. In Inner Mongolia, most rural households depend on diesel generators. Because of the high cost and the difficulties of delivery of these generators, small wind turbines are used by rural households in this region. The concept of avoiding high costs should be applied in assessing renewable energy technologies.

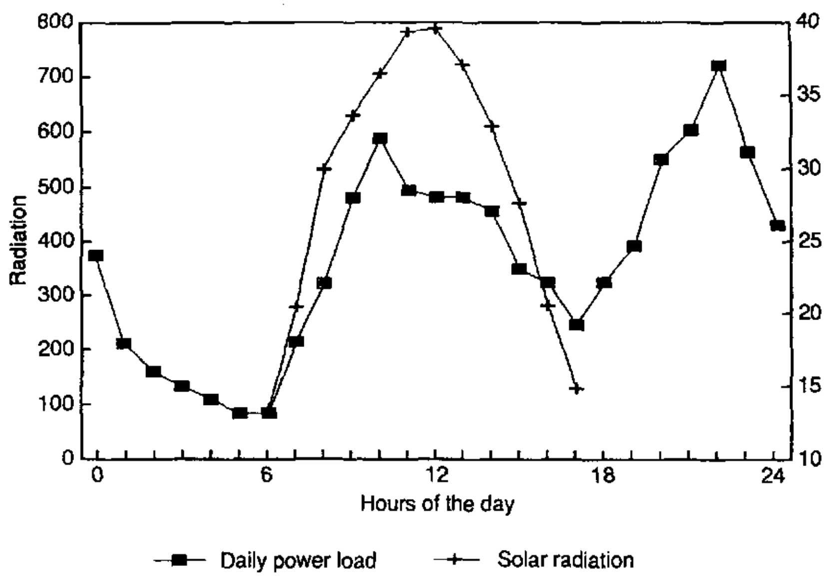

FIG. 1. Solar radiation and power load (July in Tibet).

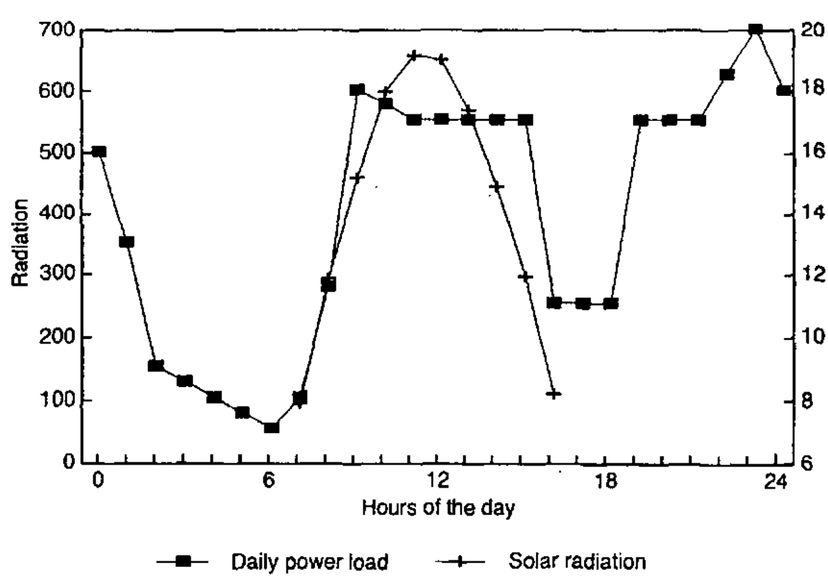

FIG. 2. Solar radiation and power load (January in Tibet).

In most cases, the supply of energy and electric power from renewable energy resources has large advantages. For example, renewable energies can be directly used by households or small businesses in rural areas, which saves construction costs for power distribution systems. In some cases, the use of renewable energy resources can replace the use of high cost suppliers of peak load. For instance, in Tibet, the available solar energy is sufficient to provide peak load power (see Figs 1 and 2). The cost of solar power generation is very high compared with that of base load power generation; however, compared with the cost of peak load power generation, the cost of solar power is relatively low. In Tibet, for example, the cost of solar thermal power generation is about 1 yuan per kilowatt-hour; in contrast, the cost of diesel power generation is about 1.4 yuan per kilowatt-hour.

According to a long term cost/benefit analysis, the cost of developing renewable energies is higher than the cost of commercial energy, especially in comparison with coal. However, on the basis of the concept of avoiding high costs, some of the renewable energy technologies are competitive with commercial energy in rural areas.

Another large benefit from the development of renewable energy technologies is the promotion of economic development in remote rural areas. For example, solar power can be used for TV systems to promote education and to provide information to the people in these areas, which will also increase their capabilities regarding economic activities. Since renewable energy technologies can help to provide energy to remote rural areas in a short time, they are competitive with conventional energy technologies, even if their cost is higher. This is one of the reasons why solar and wind power programmes have been combined with the programme for the elimination of poverty in China.

The utilization of renewable energy technologies can reduce the emission of TSPs and SO_2, which are the major pollutants from coal burning in China. Utilization of renewable energy resources will also contribute to a reduction of GHG emissions. Thus, the use of renewable energy resources in rural areas of China will result in improvement of both the local and the global environment.

5. CONCLUSIONS AND RECOMMENDATIONS

The development of renewable energy technologies is one component of the strategy of sustainable energy supply in China. Generally speaking, there are two types of approach for adopting renewable energy technologies in China. One is power generation and the other is thermal utilization of power. There are many special cases regarding the adoption of renewable energy technologies for rural electrification. Because of their high costs, most of the renewable energy technologies for power generation are subsidized by various funds, for example the Government Poverty Liberalization Fund and the Scientific and Technological

Demonstration Fund, and by some bilateral and multilateral assistance programmes. Only in a few cases, for example in husbandry farming areas, is it possible for people to buy solar or wind power equipment because husbandry farmers are usually richer than agricultural farmers in remote areas of China. However, in the long term, renewable energy technologies for power generation will not be subsidized. The major constraints to the utilization of renewable energy technologies are the high costs and the low quality of equipment, and the lack of skilled people who can take care of maintenance. Therefore, the future development of renewable energy technologies for power generation will depend on the reduction of equipment production costs, improvement of the quality of equipment and training of people. The main target of the development programme for these technologies is to overcome the above mentioned constraints. Another limitation of the utilization of renewable energy technologies is the low income of people living in rural areas. If their income could be increased, it would be possible for farmers to utilize such technologies.

For thermal use of renewable energy resources, the major constraints are connected with energy utilization and the availability of resources. Currently, the utilization of renewable energy resources in rural areas is not commercialized. Mainly biomass is used for thermal power generation, but its availability is limited. Therefore, in order to increase the thermal utilization of renewable energy resources, it is most important to increase the efficiency of energy utilization by commercialization of power production. Gasification and briquetting are the most commercialized technologies. Only by commercial utilization of renewable energy resources will it be possible to increase the total resources; the availability of biomass for use in rural areas could be doubled, since most of the commercialized renewable energy technologies can improve the efficiency of energy utilization. Thus, the potential of renewable energy utilization depends on the development of commercially viable technologies.

POTENTIAL ENVIRONMENTAL IMPACTS ASSOCIATED WITH THE CONSTRUCTION AND OPERATION OF HYDROPOWER PLANTS

N.P. VILLELA
Departamento de Meio Ambiente,
Furnas Centrais Elétricas S.A.,
Rio de Janeiro, Brazil

Abstract

POTENTIAL ENVIRONMENTAL IMPACTS ASSOCIATED WITH THE CONSTRUCTION AND OPERATION OF HYDROPOWER PLANTS.

The paper describes the main potential environmental impacts associated with the construction and operation of large size hydropower plants in Brazil. A number of preventive, mitigation and compensatory measures are traditionally adopted by the Brazilian power sector to deal with these impacts. The magnitude and the importance of environmental impacts are discussed, considering the geographical areas where the projects are located and the specific differences of the social groups affected. The environmental impacts are grouped into two main blocks, one including the physico-biotic environment and the other the socioeconomic environment; the construction stage and the operation stage of hydropower plants are discussed separately in some cases. It is concluded that the conditions in the region where the project is located, as well as the relative degree of conservation and development, are the basis for classifying the importance and magnitude of the impacts.

1. INTRODUCTION

The largest source of electric energy generation in Brazil is hydroelectricity, which represents 95% of the energy generated in this country. The remaining 5% come from thermoelectric generation, mainly from plants using coal and oil; there is only one nuclear centre, with one power plant in operation, another plant under construction and a third plant in the planning stage.

This situation is due to the large hydro potential of the Brazilian territory, as well as the small quantity and low quality of mineral coal available in this country. Thus, from economic and energy points of view, it seems to be advantageous to use the more attractive hydrographic basins, namely those of the São Francisco River and the Paraná River.

The system of generation and transmission of energy in Brazil is predominantly an interconnected one, although there are also isolated systems, particularly in the Amazon Region, where many thermoelectric plants are located.

On the one hand, economic development is beneficial for society; on the other hand, it has a number of environmental impacts, the magnitude and importance of which can vary, particularly as regards the energy generation sources and the geographical region where projects are implemented.

The environmental impacts of projects for electric energy generation, independent of the source of generation, are, of course, additional to the impacts caused by the associated transmission systems, particularly because the Brazilian electric system is an interconnected one.

The paper describes the principal impacts caused by the construction and operation of large size hydropower plants (HPP) in Brazil, but without taking into consideration the impacts of transmission lines. The main preventive, mitigating and compensatory measures against the known impacts are identified and, where possible, the magnitude and importance of regional differences are indicated.

2. LEGAL ASPECTS

Environmental legislation in Brazil is rather recent. Of particular importance is the National Environmental Policy (Law No. 6,938 of 31 August 1981), which was introduced for the purpose of ''preserving, improving and restoring a life-giving environmental quality, so as to ensure, in Brazil, conditions for socioeconomic development, for protecting national security interests and for safeguarding the dignity of human life'', as stated in its principles. Article 4, paragraph I, of the National Environmental Policy specifies that its promulgation aims at achieving compatibility of the socioeconomic development with the preservation of the environment and with an ecological equilibrium, i.e. a rational use of natural resources.

After this policy was introduced, several laws were enacted to protect the flora and fauna, the use of water resources, the native communities, and the historical, archaeological and artistic resources. Resolutions of the National Environmental Council (CONAMA) were also passed, to control the procedure of environmental licensing of polluting activities, including pertinent documentation — Environmental Impact Studies and Reports (EIA/RIMA) and the Basic Environmental Project (PBA) — as well as the appropriate environmental permits.

Among the legal instruments directly associated with this work is CONAMA Resolution No. 001, dated 23 January 1986, which establishes definitions, responsibilities, basic criteria and general guidelines for the use and implementation of the environmental impact assessment as the instrument of the National Environmental Policy.

Currently, Brazil has a special Ministry for the Environment and a subordinated National Environmental System, which has its own planning, performance and control structures for implementing the National Environmental Policy.

3. BASIC CONCEPTS

It is not intended to discuss in detail the environmental impact assessment for HPPs, but to emphasize the environmental impact caused by HPPs.

A proper definition of the word environment is fundamental to understanding and applying the concept of environmental impact. The environmental concept adopted here refers to a system with interactive factors of physical, biological and socioeconomic order. The definition of environmental impact used here is the one formulated in CONAMA Resolution 001/86, which reads: "Environmental impact is considered as any alteration of the physical, chemical or biological properties of the environment, caused by any form of matter or energy resulting from human activities which directly or indirectly may affect: the health, security and wellbeing of the population, social and economic activities, the biota, the aesthetic and sanitary conditions of the environment and the quality of environmental resources."

In generic terms, environmental impact is defined as any significant alteration of the environment — in one or more of its components — caused by human action.

The principal attributes of environmental impacts are magnitude and importance. 'Magnitude' refers to the extension of an impact caused by intervention on a specific environmental attribute in absolute terms, where basically the degree of intensity, the periodic frequency and the temporal amplitude of the impact are considered. 'Importance' measures the significance of an impact in relation to the environmental factor affected and in relation to other impacts, and depends on a judgement of value.

Several characteristics of environmental impacts are discussed in the respective literature; a few of these characteristics are listed below.

(a) Characteristics of value, representing the impact as beneficial (external action that improves the quality of the environment, also called positive impact) or as adverse (external action that impairs the quality of the environment, also called negative impact).
(b) Space characteristics, which are defined by the importance of the impact and which are different as regards locality, region or strategy (collective importance or even national importance).
(c) Temporal or dynamic characteristics, according to the time of occurrence: immediate, medium or long term, temporary or permanent.
(d) Characteristics of reversal, regarding the ability of the affected environment to return to its original conditions ('homeostasia'), i.e. classification of the impact as reversible or irreversible.

In this study we have tried to group the principal potential environmental impacts caused by the construction and operation of HPPs, according to the characteristics described here. However, we do not mention all possible environmental impacts associated with the construction and operation of HPPs, but we treat them generically, even if omissions may occur. Thus, the impacts identified in large Brazilian power plants have been adopted as standard, with additional considerations related to the geographic area in which the projects are located and the specific conditions of the different social groups affected.

4. ENVIRONMENTAL IMPACTS DURING CONSTRUCTION AND OPERATION OF HPPs

To be able to discuss the environmental impacts of HPPs, it is necessary to know the overall environmental context of such projects. The environmental impacts of HPPs can be evaluated in six stages.

Stage 1

Environmental characteristics of the region influenced by the project: environmental diagnosis.

Stage 2

Identification of the main environmental impacts when the project is introduced: impact selection.

Stage 3

Evaluation of the environmental impacts identified, considering the social groups affected, the legislation and the rules in force, and sectorial guidelines: estimated magnitude of the impacts and establishment of their importance.

Stage 4

Identification of preventive, mitigating and compensatory measures: correction or reduction of the magnitude of the impact.

Stage 5

Application of the identified measures: basic environmental project.

Stage 6

Environmental monitoring and evaluation of the result of the measures taken: study of the effectiveness of the measures.

The construction period of an HPP considered here is from the initial land movement, etc., for the dam site to the start of operation of the first device; this includes the filling of the reservoir, which is the activity that has the largest impact on the environment. The period between startup of operation of the first device and the end of the working life of the plant is called the operating stage.

The main potential environmental impacts resulting from the construction and operation of HPPs are summarized in Table I. However, the range of environmental impacts is by no means limited to those associated with this category of projects; these impacts can vary according to the location of the plants. The items presented in Table I are discussed in the following sections.

4.1. Impacts on the physico-biotic environment

The environmental impacts on the physico-biotic environment during the construction and operation of HPPs are largely due to the building of dams in rivers to form reservoirs, which transform the natural lotic (running) waters to lentic (still) waters.

4.1.1. Hydric resources

(a) *Alteration of the course of the river.* Diverting a river from its original course to clear the area where the dam will be built is the basic condition for building HPPs. Although this diversion does not imply an alteration of the river flow, other impacts of lesser magnitude may occur, particularly impacts on the freshwater fauna (to be dealt with later).

(b) *Increase in turbidity.* The movement of soil during the construction of the power plant leads to a discharge of solid particles and makes the water more muddy. Engineering measures of a preventive nature may be taken during the construction of the HPP to reduce the magnitude and importance of this impact.

(c) *Reduction of the downstream water flow.* The National Department of Waters and Electricity (DNAEE) published Ordinance No. 25, dated 17 August 1993, which reads: "In the course of developing the studies and conception of the Basic Project it should be considered that the remaining flow of the water course downstream should not be less than 80% of the average monthly minimum flow, based on the historic sampling of natural flows for at least 10 years. The cases where it is impossible to apply the above specified criteria, as well as those of serial reservoirs, shall be examined by DNAEE." In practice, it is not always possible to maintain the required flow of the downstream water course, since this is determined by the technical and energetic characteristics of the projects. This causes significant impacts on the areas downstream of the dam; these impacts are related to the contributing water system and the duration of reduced flow. Such impacts can be avoided by taking them into account at the planning stage, or they can be reduced by engineering measures that guarantee minimum sanitary and ecological discharges into the river, for example by providing a bottom outlet.

Text continued on page 165.

TABLE I. SUMMARY OF THE MAIN POTENTIAL ENVIRONMENTAL IMPACTS RESULTING FROM THE CONSTRUCTION AND OPERATION OF HYDROPOWER PLANTS

Environmental attribute	Event generating the impact	Nature of impact	Moment of occurrence of the impact[a]	Value of the impact[b]	Intensity of the impact	Time and duration of the impact	Reversibility of the impact	Preventive, mitigating and compensatory measures
Hydric resources	Deviation of the river	Alteration of the course of the river	C	A	Local	Immediate	Irreversible	None (basic condition for construction of the power plant)
	Movement of soil	Increase in turbidity	C	A	Local	Medium term	Reversible	Engineering measures to reduce the discharge of solid materials into the hydric resource
	Closure of flood gates of the deviation tunnel(s) ↓	Alteration of the discharge downstream of the dam	C	A	Variable[c]	Temporary	Reversible	Engineering measures (e.g. bottom outlet)[c]
	Filling of the reservoir	Alteration of the water condition from lotic to lentic	O	A	Regional/ strategic[d]	Permanent	Irreversible	None (basic condition for construction of the power plant)
		Change of the water quality	C/O	A	Regional[c]	Medium/long term[a]	Reversible	Project alternatives Engineering measures Control of soil usage around the reservoir

[a] C — construction; O — operation. [b] A — adverse, B — beneficial. [c] Depends on the project characteristics. [d] Depends on the geographical location of the project.

Hydric resources (cont.)	Reservoir formed	Attenuation of flood peaks	O	A/B	Regional	Permanent	Reversible	Adaptation of operating rules of the plant
		Elevation of underground water	O	A/B	Regional	Permanent	Irreversible	None (basic condition for construction of the power plant) Monitoring of underground water level
Underground thermal water	Filling of the reservoir	Cooling of the hydrothermal aquifer	O	A	Regional/ strategic[d]	Permanent	Irreversible	None (basic condition for construction of the power plant) Hydrothermal monitoring
Climate	Reservoir formed	Influence on the local climate	O	A/B	Local	Permanent	Irreversible	None (basic condition for construction of the power plant)
Relief	Filling of the reservoir	Changes of the natural landscape	C/O	A/B	Local	Permanent	Irreversible	None (basic condition for construction of the power plant)
Soils and mineral resources	Construction of the dam	Land movement	C	A	Local	Short/medium term	Irreversible	None (basic condition for construction of the power plant)
	Filling of the reservoir	Flooding of soils and mineral resources	C	A	Local/ strategic[d]	Immediate	Irreversible	Maximum use of mineral resources and soil

TABLE I (cont.)

Environmental attribute	Event generating the impact	Nature of impact	Moment of occurrence of the impact[a]	Value of the impact[b]	Intensity of the impact	Time and duration of the impact	Reversibility of the impact	Preventive, mitigating and compensatory measures
Soils and mineral resources (cont.)	Reservoir formed	Soil erosion on the borders of reservoirs	O	A	Local	Medium/long term	Reversible	Control of soil usage around the reservoir Reforestation of critical areas
		Erosion of 'loaned' soil and erosion of downstream soil	O	A	Local	Medium/long term	Reversible	Recomposition of tallus Vegetative recuperation
		Aggradation of the reservoir	O	A	Local	Medium/long term	Reversible	Control of soil usage around the reservoir Adaptation of operation rules of the plant
Seismicity	Construction of the dam and filling of the reservoir	Induced seismic disturbance	C/O	A	Variable[c]	Short/medium /long term	Irreversible	Engineering measures to guarantee the safety of the dam Seismological monitoring
Flora	Filling of the reservoir	Deforestation	C	A	Local	Immediate	Irreversible	Economic use of the flora (timber extraction)
		Submersion of the vegetation	C	A	Local	Immediate	Reversible	Deforestation Rescue of germ-plasm Creation of a Conservation Unit

Fauna	Filling of the reservoir	Loss of territory	C	A	Local/ regional	Immediate	Reversible	None (basic condition for construction of the power plant)
		Pressure on the existing fauna around the lake	C/O	A	Local/ regional	Short/medium term	Reversible	Induced displacement of fauna Rescue of fauna Delimination of areas with the capacity to support the displaced fauna Creation of a Conservation Unit
Aquatic fauna	Deviation of the river	Loss of zoobenthic fauna living on the part of the river that was drained	C	A	Local	Immediate	Irreversible	None (basic condition for construction of the power plant)
	Damming of the river	Impediment of migratory movement of fish	C/O	A	Regional[d]	Permanent	Variable[c]	Construction of devices for fish to cross the dam
	Reservoir formed	Alteration of the specific composition	O	A/B	Regional[d]	Medium/long term	Irreversible	Repopulation of the reservoir
		Reduction of fish stocks	O	A	Regional[d]	Medium/long term	Reversible	Repopulation of the reservoir Net tanks
		Disappearance of downstream beaches	O	A	Regional	Medium/long term	Reversible	Building artificial beaches

TABLE I (cont.)

Environmental attribute	Event generating the impact	Nature of impact	Moment of occurrence of the impact[a]	Value of the impact[b]	Intensity of the impact	Time and duration of the impact	Reversibility of the impact	Preventive, mitigating and compensatory measures
Conservation Units	Filling of the reservoir	Flooding of Conservation Units	C	A	Local	Immediate	Reversible	Purchase of areas preferably contiguous to the Conservation Unit
Population	Filling of the reservoir ↓	Compulsory displacement of the rural and urban population	C	A	Local	Immediate	Reversible	Resettlement of the population Relocation of cities Implementation of compensatory measures
	Reservoir formed	Intensification/ reduction of the population flow	C/O	A	Local/ regional	Medium/long term	Reversible	Control of the migratory flow of people by monitoring
		Adaptation of the population to the new living conditions	O	A	Local/ regional	Short/medium /long term	Reversible	Monitoring and assistance of the population
Indian communities and other ethnic groups	Construction of HPPs	Interference with the indian population and other ethnic groups	C/O	A	Local/ strategic	Immediate	Irreversible	Implementation of compensatory measures

Public utilities	Filling of the reservoir	Flooding of rural and urban public utilities	C	A	Local/ regional	Immediate	Reversible	Relocation of public utilities
	Migratory flow	Exceeding the capacity of public utilities	C	A	Local/ regional	Temporary	Reversible	Enlargement of the existing services
Infrastructure	Filling of the reservoir	Flooding of the infrastructure	C	A	Local/ regional	Immediate	Reversible	Relocation of the infrastructure
Economic activities	Filling of the reservoir ↓	Flooding of areas destined for cattle raising and extraction activities	C	A	Local/ regional/ strategic[d]	Immediate	Irreversible	Maximum use of the natural resources in the area to be flooded
	Construction of HPPs	Flooding of industries	C	A	Local/ regional/ strategic[d]	Immediate	Reversible	Relocation of industries Location of other areas containing the raw material required by the industry
		Changes of activities in cities	C/O	A/B	Local	Immediate	Reversible	Control and/or enlargement of the existing services
	Reservoir formed	Loss of collected tax revenue	O	A	Local/ regional	Immediate	Reversible	Financial compensation

TABLE I (cont.)

Environmental attribute	Event generating the impact	Nature of impact	Moment of occurrence of the impact[a]	Value of the impact[b]	Intensity of the impact	Time and duration of the impact	Reversibility of the impact	Preventive, mitigating and compensatory measures
Public health	Migratory flow	Spread of exogenous and endemic diseases	C/O	A	Local	Medium/long term	Reversible	Establishing programmes to prevent epidemics
	Filling of the reservoir	Accidents with poisonous animals	C	A	Local	Immediate	Reversible	Establishing information programmes Special caution during the filling of the reservoir
	Reservoir formed	Incidence of hydrically propagated diseases	O	A	Local	Medium/long term	Reversible	Establishing measures to control vectors
Prehistorical and historical archaeological patrimony	Filling of the reservoir	Interference with the prehistorical and historical archaeological patrimony	C	A	Local	Immediate	Reversible	Registration, prospecting and excavation of patrimonial sites and buildings

The magnitude and importance of such impacts are directly related to the extension of the area receiving a smaller amount of water from the tributary rivers; they also depend on the use and occupation of the soil in this area.

(d) *Alteration of the water condition from lotic to lentic.* In order to be able to generate substantial quantities of energy from hydropower, it is necessary to build a reservoir; the impacts of this persist throughout the entire working life of the plant. Small HPPs, which do not have reservoirs and which operate by run of river do not cause this type of environmental impact.

(e) *Change of the water quality.* Filling of a reservoir causes immediate changes of the water quality of the main river in which the reservoir is located and consequently of the water downstream of the dam. This was confirmed by monitoring studies of the filling stage of reservoirs of some Brazilian power plants. In the course of the operation of the power plant, the limnological parameters and those of the water quality will tend to stabilize after the formation of the reservoir. Some measures can reduce the intensity of this impact, but its occurrence is inevitable. The magnitude and importance of the impact tend to increase, particularly in anthropic regions.

When the reservoir is formed, the limnological and water quality parameters tend to stabilize. Their characteristics depend basically on the use of the soil along the borders of the reservoir and on the morphological characteristics, the period of residence of the water in the reservoir, the water depth and the average depletion. Measures of quality control of affluents into the reservoir will minimize the deterioration of the water in the reservoir. Other measures of a technical nature, for instance the installation of aeration units along the reservoir in order to increase the amount of oxygen dissolved in its water, are considered to be effective only for small reservoirs because of the high cost involved. The magnitude of the impact is large and may become larger downstream of the dam. The same applies for the importance of the impact, since the reservoir may also be used for purposes other than energy generation.

(f) *Attenuation of flood peaks.* Impacts of this nature may be classified as beneficial or adverse, depending on the hydrographic basis and on the degree of development of the region affected by the work. In areas where many people live on the banks of rivers or reservoirs, the control of natural floods by damming the river may be beneficial, whereas the interruption of floods may have a large impact on the ichthyofauna (fish) and on fishing activities in this area.

(g) *Elevation of underground water.* The influence of HPP reservoirs on underground water is either beneficial or adverse, depending on the regional edapho-climatic conditions. In dry areas, for example in the north-eastern parts of Brazil, positive changes of the soil characteristics may occur, which will improve the living conditions of the population in these areas. In areas with large population groups, elevation of underground water may cause floods, which have a prejudicial impact on the population. The effects of such an occurrence are permanent and irreversible, and they should be investigated already during the planning stage of the project.

4.1.2. Underground thermal water

The influence of reservoirs of HPPs on underground thermal water is a regional impact. In Brazil, no cases with significant impacts are known; however, a study is being performed of the interaction of a power plant under construction with the thermal aquifer of a small town, which has attracted tourists for a long period. Studies of the recharging area of the aquifer, of the way it works and of its current piezometric level can provide the required basic information on the occurrence of an impact. The magnitude and importance of such an impact depend on the geological conditions of the aquifer and its economic utilization.

4.1.3. Climate

The influence of reservoirs on the local climate is a highly controversial issue. Climatic studies performed so far for Brazilian power plants have shown that there may be changes to the local climate, but that they have no influence on the regional climate.

Interpretative studies of data generated by the meteorological stations of the Itaipu HPP before and after formation of the reservoir showed a small rise in the temperature (although statistically irrelevant), and an increase in the relative air humidity and the wind velocity, which were limited to the towns near the reservoir. The magnitude of the impact depends on the extent of the reservoir, and the importance of the impact depends on the local climatic characteristics.

4.1.4. Relief

Reservoirs change the natural landscape of a region, causing significant transformations of the relief — from the disappearance of valleys to the formation of 'islands' (remains of mountains). The magnitude of these impacts is large and their importance is directly related to the economic and cultural use of the flooded areas, particularly the valleys.

4.1.5. Soils and mineral resources

The impact of the construction of an HPP on the soil and on mineral resources is due to the use of the soil for the construction of the dam and the potential loss of land when the reservoir is formed. The magnitude and importance of the impact depend directly on the present and potential use of these resources and even on their strategic value on a national basis. In the case of the Serra da Mesa HPP, which is under construction in the central-western region of Brazil, the magnitude of the impact was large. This project had to be altered in order to avoid interference with an important uranium reserve. Economic problems associated with soil and mineral resources are discussed below.

The impact on these resources during plant operation is subdivided into the following four categories:

(a) *Soil erosion on the borders of reservoirs.* Incorrect utilization of the borders of reservoirs and the operation rules of the power plant are important factors regarding erosion processes, which greatly contribute to the aggradation of the lake and to loss of land. The magnitude and importance of these impacts depend upon the characteristics and usage of the soil, the operation rules of the power plant and the representativeness of the vegetation belt along the borders of the lake. Measures for controlling erosion processes and recuperation of vegetation in critical parts on the borders of reservoirs can reduce the intensity of this type of impact.

(b) *Erosion of 'loaned' soil.* Recuperation of 'loaned' areas, if performed inadequately, causes significant impacts, which may last a long time and which may increase. This is the case with the Itumbiara HPP, located in Brazil's south-eastern region. The plant, which has been in operation since 1981, did not recuperate one of its loaned areas, and this caused a gully of approximately 300 m × 120 m. Recuperation programmes for loaned areas, including recomposition of talus and vegetative recuperation, greatly reduce the impact. The magnitude of this impact is related to the size of the area to be used, and the importance of the impact may be reduced by adopting technically appropriate measures.

(c) *Erosion of soil downstream of a dam.* The operation of the spillway of an HPP, which is associated with the characteristics and the usage of the soil downstream of the dam, may cause a landslide of the river banks (similar to what happened at the Itumbiara HPP). The importance and magnitude of the impact are directly related to the size of the affected area and to its use.

(d) *Aggradation of the reservoir.* Suspended solids carried by the tributary rivers forming the reservoir and incorrect use of the borders of the reservoir cause a reduction of the volume of water, which is the determining factor of the plant's working life. The Brazilian environmental policy has declared the natural vegetation on the borders of reservoirs along a belt of 100 m to be the subject of permanent forest preservation; this reduces soil erosion and consequently aggradation of the lake. However, in practice, there is not always a natural vegetation in this area. On the other hand, plant operation causes a depletion of the reservoir waters, which, depending on the characteristics of the land, can influence large areas, for instance about 40 m, as in the case of the Serra da Mesa HPP. This contributes to the erosion processes and the consequent aggradation of the lake.

4.1.6. Seismicity

Seismic disturbances induced by the construction of dams has been the subject of many discussions. The importance and magnitude of these impacts are large in regions where such natural disturbances occur with great intensity. In the Brazilian territory there are practically no such disturbances and the registered seismic events are of small magnitude on the Richter Scale. Nevertheless, before the construction of large dams, seismic monitoring of the region is always performed and it is continued during the whole period of plant operation.

4.1.7. Flora

The impact on the flora (vegetation) begins with deforestation before filling of the reservoir; if there is no deforestation, the impact on the flora is due to its submersion. The magnitude of the impact depends basically on the size of the reservoir area and on the state of conservation of the region to be flooded. The importance of this impact, however, depends mainly on the geographical area where the project is located. The utilization of areas considered as national patrimony by the 1988 Brazilian Constitution (Amazon Forest, Matogrosso Swamps, Atlantic Forest, Mar Hills and Coastal Zone) is defined by law, which results in a certain 'restriction' on their use for energy generation and transmission. Aside from this aspect, which is of a legal nature, there is also the aspect of loss of scientific knowledge and loss of genetic matter of unknown vegetal species or even species that are threatened with extinction.

In order to reduce the impact on the flora, studies of the floristic composition of vegetal species are performed, as well as conservation actions, such as the rescue of germ-plasm for genetic conservation, the supply of existing germ-plasm banks aiming at 'ex situ' conservation, and the creation of a forest arboretum for 'in situ' conservation of germ-plasm.

Actions of an economic nature are sometimes taken, in order to use the wood potential of the area to be flooded. Floristic surveys of this potential and of the impact of further deforestation are made. When deforestation is planned, not only economic aspects are considered but also aspects of health, aesthetics, power plant safety, as well as other potential uses of the reservoir.

Finally, conservation of the flora can be achieved by creating a Conservation Unit[1] in areas having characteristics similar to those of the affected area.

The impact on the vegetation during operation of a power plant depends on the capacity of the vegetal species located on the borders of the reservoir to adapt them-

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[1] Conservation Unit is a generic term referring to all categories of protected areas established by law (e.g. biological reserves, ecological stations, national parks).

selves to the new environment and to collect underground water. In regions of scarce vegetal coverage the impact is negligible. On the other hand, in preserved regions, such as the Amazon Forest, this impact is of great importance and magnitude, since the new 'cilliary' vegetation has characteristics which are different from those of the typical vegetation of this environment.

4.1.8. Fauna

The influence of HPPs on the fauna should be evaluated in conjunction with the influence on the flora. The impact on fauna caused by the construction of a reservoir for an HPP is connected with the loss of territory that provides food and is used for reproduction, as well as the pressure on the fauna existing around the reservoir, which will compete with the displaced fauna. The importance of endemic species and those which are threatened with extinction should be noted.

The magnitude and importance of the impact on the fauna are the same as those of the impact on the flora, except for some special measures that are traditionally taken at Brazilian HPPs. The composition of the fauna and its population dynamics are studied, considering the possibility of displacement of the fauna to emerging land or to areas that are capable of supporting the displaced fauna.

As in the case of the flora, conservation of the fauna can be achieved by creating a Conservation Unit in an area with characteristics similar to those of the affected area.

During plant operation, monitoring of the fauna is performed in order to enable the new situation to be diagnosed, so that the remaining fauna can be adequately treated. The magnitude and importance of the impact depend on the state of conservation of the region influenced by the project and on the degree of representativeness of the affected ecosystem.

4.1.9. Aquatic fauna

(a) *Ichthyofauna.* The principal representatives of the aquatic fauna in the area affected by the construction of an HPP are fish (ichthyofauna); their natural habitat is totally changed. Damming of rivers to form reservoirs prevents migratory movement of fish, and spawning areas are often isolated from areas for juvenile fish. The magnitude of the impact on the ichthyofauna is great; it is a function of the transformation of the hydric resource from lotic to lentic. The importance of the impact is largely associated with endemic species and those threatened with extinction, as well as with the fishing activities in the region. In the course of plant operation, species that can better adapt themselves to lentic environments will grow, to the detriment of reofilic species, which usually have a higher commercial value. In addition, the regulation of the discharge influences mainly the reproduction of the different species in downstream areas, causing reduction of fish stocks.

(b) *Zoobents*. Zoobenthic fauna (the fauna which depends on substrates for survival) is affected by the impact on the part of the river that was drained before the construction of the dam. The magnitude and importance of this impact are of little significance; a positive aspect of it is that it is possible to obtain a better knowledge of the benthonic fauna occupying large river beds. The addition of sediment to the water downstream of the dam may also have an impact on the zoobents because of the change in granulometry. At the operating stage of the plant, species of freshwater turtle using the beach for reproduction may be affected; this is very common in the Amazon region. The reservoir works as a 'filter', retaining part of the suspended solids, which are normally carried by the river water and which form beaches. When the dam is built, these suspended solids no longer contribute to the formation of a beach. Evidently, the absence of such places causes disappearance of the species that depend on them for survival.

4.1.10. Conservation Units

Conservation Units are part of the national territory, with relevant characteristics, of either public or private property, legally established by the Government, with defined objects and limits, and covered by adequate protectionary guarantees. Hydropower plants have an impact on these units when their territories or parts thereof are flooded. The magnitude and importance of this impact are directly related to the size of the affected area and the category of the Conservation Unit. The Brazilian System of Conservation Units has grouped them into three different categories: units of total protection, units of temporary conservation and units of sustainable management, with different restrictions on usage.

4.2. Impacts on the socioeconomic environment

Impacts related to the socioeconomic environment are mostly due to the formation of reservoirs and the flooding of land.

4.2.1. Population

(a) *Compulsory displacement of the rural population*. Flooding of land in rural areas for the purpose of building HPPs interferes with the residing population which normally depends on the land for making a living. The magnitude of the impact on the population depends on the number of families living in the area. The importance of the impact depends on the links of the population with the land, the influence of the lake on the physico-territorial organization and on the social, political and cultural aspects, as well as on the availability of land close to the reservoir where the affected population can live. Programmes for population resettlement and other compensatory actions are being negotiated with the affected population.

(b) *Compulsory displacement of the urban population.* Flooding of urban centres or parts of them leads to compulsory displacement of people and interferes with the physico-territorial organization and the social, political and cultural organization of the population. The magnitude and importance of the impact are usually large, not only because of the economic aspect of relocation of cities but also because of cultural values. Relocation of urban communities is traditionally carried out by the Brazilian power sector, as was recently done in connection with the Nova Ponte HPP located in the south-eastern region of Brazil.

(c) *Adaptation of the population to new living conditions.* One of the most challenging issues in planning HPPs is the impact on people living in rural areas, particularly those with low incomes who do not own the land on which they make their living and who do not always manage to adapt themselves to the new way of life. Furthermore, they suffer from the cultural transformation in connection with the displacement caused by the installation of the power plant.

Depending on the region of the country, the magnitude and importance of this impact may be very large. This was the case with the Itaparica HPP, built in the north-eastern region of Brazil, where approximately 5500 rural families had to be resettled in places with characteristics different from those in their previous residence. They had to take up activities different from those to which they were accustomed. Some of these people still depend on financial help from the company operating the plant (the power plant is in operation since 1988); this has become a source of great conflict in the region. Population groups with greater purchasing power tend to look for other options without large problems.

Urban communities also have to adapt to the changed circumstances. The Brazilian power sector has great experience with relocating towns and cities; positive results have been achieved when the affected people were consulted before relocation.

(d) *Enlargement or reduction of the population flow.* HPPs usually attract those people who are in search of employment or who want to establish trade and services. Monitoring of the migratory flow is important for preventing a major impact. The importance and magnitude of the impact depend on the intensity of the migratory flow and the capability of the plant operator to control it.

When the construction of the power plant is finished, the migratory flow of people declines because of the reduction in employment opportunities. This impact is more significant in urban centres where the offered trade and services begin to exceed the demand. If preventive control of this flow is exercised, the magnitude and importance of this impact may not be significant.

4.2.2. Indian communities and other ethnic groups

The Brazilian Constitution of 1988 established that the "use of hydric resources, including the energetic potential, survey for extraction of mineral resources found in indian territory, can only be authorized by the National Congress, when previously informed by the affected communities, with an assured participation on the results obtained with the extraction efforts, in accordance with the law." It also established as 'registered', "all documents and places that hold historical reminiscences of old hiding places of fugitive negro slaves" ('quilombos').

As a result of this Constitution, the impacts caused by the construction of HPPs in indian territories, as well as in territories of other ethnic groups, are of large magnitude and importance, demanding complex negotiations for their solution. Compensatory programmes for these communities include measures adopted to deal with these impacts; in practice, the plant operators take on the responsibility for these communities during the entire operating life of the projects. As an example of the degree of complexity of dealing with this kind of impact, the Foz do Bezerra HPP, which is in the planning stage, in the central-western region of Brazil, had to change the location of the dam in order to avoid occurrence of a large impact on a 'Kalunga' community (an ethnic group).

4.2.3. Public utilities

(a) *Flooding of public utilities in rural areas* (churches, schools, cemeteries). The magnitude and importance of this impact depend on the region and on the size of the area to be flooded in order to form a reservoir, as well as on the costs for relocation. For example, relocation of cemeteries is of great cultural importance; in the case of the Dona Francisca HPP, in the south of the country, five cemeteries were affected, and large efforts were made to resettle them.

(b) *Flooding of public utilities in urban areas.* The magnitude and importance of this impact are very significant because of the changes connected with the construction of new urban centres. The success of relocation depends mainly on the participation of the affected population in the definition of the criteria for relocation.

(c) *Exceeding the capacity of public utilities.* Because of the migratory flow of people the capacity of the school system is often exceeded; also, the demands for new houses and for water and sewage services, etc. cannot be satisfied. The existing services may have to be enlarged, depending on the extent of the impact, which may result in high costs. The magnitude and importance of this impact depend on the dimension of the new demand.

4.2.4. Infrastructure

The road system is normally the infrastructure that is most affected by the formation of reservoirs in rural areas; this system consists of federal roads, railways, monuments, bridges, stations, etc. The magnitude of the impact depends on the number of kilometres, the size of monuments, etc. to be flooded, and the cost for their relocation, regardless of their actual importance. It should be noted that, depending on the region, this impact may have significant proportions and may increase the investment cost. Examples are the Serra da Mesa and the Sapucaia HPPs, with reservoir areas of 1784 km^2 and 6.8 km^2, respectively, for which relocation costs of US \$40 $\times 10^6$ and 20 $\times 10^6$ have been estimated. This shows that the magnitude and importance of the impact do not depend on the size of the area to be flooded but on the degree of development of the region. Programmes for relocating the infrastructure are traditionally performed by the Brazilian power sector, with satisfactory results.

4.2.5. Economic activities

(a) *Flooding of economic areas (primary sector).* The use of land for building and operating HPPs interferes with the activities related to the primary economic sector; in other words, it interferes with cattle raising and with extraction activities (vegetal and mineral). The impact on these activities affects the living conditions of people who depend on them — a factor indicating the importance of the impact. The magnitude of the impact is related to the current utilization of the affected area. Another impact on economic activities is renouncing the use of potential goods, such as mineral resources, which are still under survey and which have not yet been explored. One of the measures traditionally taken to minimize this impact is the introduction of methods to guarantee exploration of the natural resources before filling of the reservoir.

(b) *Flooding of industries (secondary sector).* The impact on industries is due to the flooding of their physical structure or of the required raw material. This problem can be solved by relocating the industrial facilities, and the importance of the impact can be minimized by providing an area where the required raw material is available in sufficient amounts. This was possible in the case of the Igarapava HPP, which is under construction in the south-eastern region of the country; an alternative deposit of clay was found that was used for the brick factories of the region.

(c) *Changes of activities in cities (tertiary sector).* The impact concerns urban centres. An alteration occurs in the offer and demand for services and in the trading activities in such centres, particularly those that offer support for the construction of the plant even though they are not located in the area directly affected. Increases in prices of services and commercial items as a result of the higher demand are very common.

(d) *Loss of collected tax revenue.* This impact occurs in all sectors of the economy; the magnitude and importance of this impact are related to the dimension of the impact. In 1989, Brazilian Law No. 7,990 was passed, which laid down financial compensation for those States, federal districts or towns in whose territory installations for the production of electric energy are located or where areas were flooded for the purpose of building reservoirs.

4.2.6. Public health

(a) *Spread of exogenous diseases.* The migratory flow of people resulting from the construction of an HPP may lead to diseases that are not endemic to the affected region, which changes the overall sanitary situation of the region. Programmes for preventing epidemics are enforced in order to reduce the magnitude of the impact, the importance of which can be great. Workers on such projects have to undergo special examinations.

(b) *Spread of endemic diseases.* The migratory flow of people may also lead to the spread of diseases that were so far endemic to the affected region. Programmes similar to those adopted for exogenous diseases are also carried out in this case.

(c) *Accidents with poisonous animals.* When a reservoir is filled, poisonous animals from the flooded area may reach inhabited areas and hurt people. It is important to inform the affected population and to advise them on how accidents can be prevented. The magnitude of the impact depends on the state of conservation of the area where the power plant is located and on the characteristics of the reservoir, particularly its dimensions and how long it has taken to fill.

(d) *Incidence of hydrically propagated diseases.* The most significant impact in the area of health, throughout the operation of the power plant, is the appearance and/or increased incidence of hydrically propagated diseases. The new conditions brought about by the reservoir facilitate the development of vectors that did not have adequate conditions before, which may lead to alarming situations. A classical example of this is the Tucurui HPP, in the north of Brazil, where about one year after filling of the lake the Mansonia mosquito proliferated in some areas of the left bank of the lake. At present, this is the most serious health problem in the region of the reservoir. Evidently, the impacts in regions with ideal characteristics for development of such vectors tend to be of large magnitude and importance.

4.2.7. Prehistorical and historical archaeological patrimony

(a) *Interference with the prehistorical archaeological patrimony.* This patrimony refers to all evidence of human occupation in the prehistorical period. In the case of Brazil, this period is associated with the country's discovery, i.e. the time before the year 1500. The impact of building an HPP normally occurs when the land formerly occupied by prehistorical human groups is flooded. Identification of archaeological sites and their immediate registration, as well as prospecting and excavation work to reconstruct the historical process of bygone populations are the preventive measures adopted to mitigate the impact. The magnitude of the impact depends on the occurrence of archaeological sites, and the importance of the impact is related to the understanding of the cultures over historical times.

(b) *Interference with the historical archaeological patrimony.* In Brazil this patrimony relates to the period after the year 1500. This patrimony usually consists of ruins that can be easily identified. Inventories of historical buildings in the area influenced by the project are made, as well as photographic and digital registers of the identified sites. In some instances, these historical buildings were relocated to places outside the affected area. This was the case with a farm's main house, in the area of the Nova Ponte HPP. The magnitude and importance of the impact depend on the same points as mentioned for the prehistorical archaeological patrimony.

5. CONCLUSIONS

The environmental impacts associated with the construction and operation of HPPs in Brazil have been discussed. The subject is in itself quite complex and it is difficult to provide a simple analysis; also, some impacts may have been omitted by the author because they did not seem to be relevant.

The impacts of HPPs are of different types; they begin already at the planning stage and in some cases they last throughout the entire operating life of the plant.

The quality of the environment is not the same in the different parts of the Brazilian territory. The conditions in the region where the project is to be developed are the basis for classifying the magnitude and importance of the expected impacts. Also, the state of conservation and development of each region will determine the degree of the importance and the magnitude of the impacts.

Furthermore, there are legal aspects which usually increase the complexity of the problems and make their solution more difficult. This degree of complexity can vary, depending on the existing Government laws and other legal instruments that regulate the use of natural resources in every country, State or town.

PSYCHOSOMATIC AND SUBSTITUTIONAL EFFECTS
Comparative health risks from electricity generation

N. POP-JORDANOVA
Faculty of Medicine,
University of Skopje

J. POP-JORDANOV
Research Centre for Energy and Informatics,
Macedonian Academy of Sciences and Arts

Skopje, The Former Yugoslav Republic of Macedonia

Abstract

PSYCHOSOMATIC AND SUBSTITUTIONAL EFFECTS: COMPARATIVE HEALTH RISKS FROM ELECTRICITY GENERATION.

In contrast to standard health risk analyses, which are restricted to somatic diseases induced by physical and chemical agents, the paper considers also somatic diseases induced by psychological agents. Consequently, a concept of 'psychological pollution' from energy and other industrial systems is postulated and verified for coal fuelled and nuclear power systems. The investigations concerning the staff of the Macedonian coal fuelled power plant Bitola and the Slovenian nuclear power plant Krško indicated an increased incidence of psychosomatic diseases, with peptic ulcers and arterial hypertension being particularly pronounced. An additional effect, which decreases the standard risk values, is 'substituted pollution', which denotes the risk from replaced materials and other sources of hazards. This correction of the standard risk values should be applied for solar, nuclear and hydro plants. The need for further research is emphasized and some modifications to standard health risk approaches are suggested; these concern the definition of environment by the World Energy Council, the generalized risk pathway and management scheme, as well as the response measures by electric utilities and decision makers.

1. INTRODUCTION

An important and urgent universal problem of today is how to supply enough energy without unacceptable damage to health and the environment.[1] In this

[1] A recent definition of environment by the World Energy Council (WEC) [1] is "All the physical, chemical and biological agents together with the social factors capable of having a direct or indirect effect, immediately or in the long run, on living organisms and human activities considered in a given timeframe". In this sense, the common syntagma 'health and the environment' appears to be somehow obscure, adding one particular object (health) to the whole sum of the agents (environment).

respect, health risk analyses and comparisons can provide valuable knowledge that can be used to improve plant safety as well as energy policy and decision making.

Current methods for comparative health risk assessment of different energy systems have been reviewed on several occasions, underlining the need for further developments. In particular, the necessity of more comprehensive approaches, covering various specific dimensions of health impairment, has been pointed out [2–6]. In this paper, some additional holistic effects, relevant to comparative health risks from electricity generation, are considered. One effect is related to the concept of 'psychosomatic risk' as a supplementary health risk component and another effect concerns the 'substituted risk' as a compensating element.

2. STANDARD APPROACH

2.1. Results from comparative health risk assessments

Figure 1 summarizes typical results from comparative health risk assessments of different electricity generating systems. A common health risk indicator (man-days lost per megawatt-year, i.e. MDL/MW·a) is used, where one fatality is supposed to be equal to 6000 man-days lost owing to injury or disease. Also, all stages of the fuel cycle and the plant life are included (from mining to waste disposal and from plant construction to dismantling). The indicated relatively large band-widths illustrate the range of uncertainties and the variations among different compilations of data.

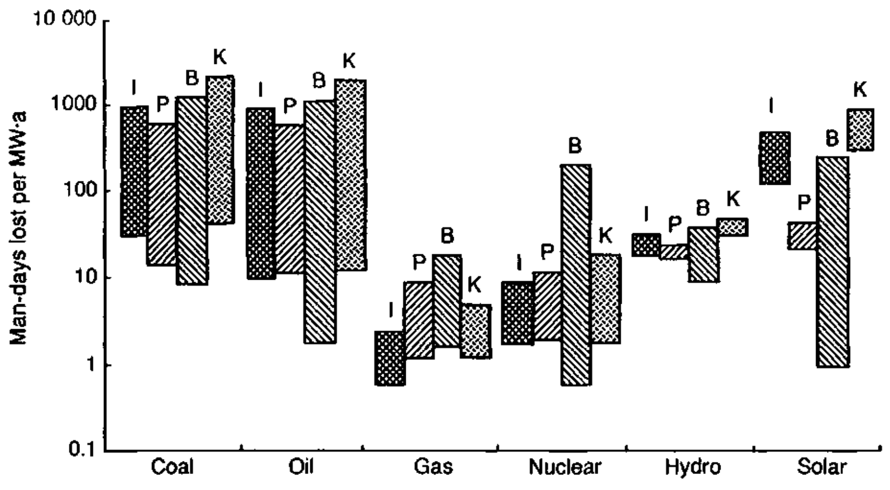


FIG. 1. Standard health risk values for different energy systems.
I — Inhaber [7], P — Pop-Jordanov [8], B — Birkhofer [9], K — Kollas and Papazoglou [10].

The highest health risks from coal plants are estimated to be occupational risk at the stage of mining and public risk at the stage of energy generation (due to atmospheric pollutants). A similar reasoning holds for oil, especially at the generation stage (public). Electricity generation from natural gas and nuclear energy is characterized by the lowest level of health risk; this is mainly due to the low emissions of pollutants for natural gas and the high energy density of fuel in the case of nuclear power. The relatively high risk level of hydropower is mainly due to the rather frequent accidents with dams, and that of solar energy is due to the large amount of material required at the pre-operational stages and the assumed necessity of a coal plant as an intermittent backup system.

In all the above health risk analyses, only somatic diseases induced by physical and chemical agents are considered. Our starting hypothesis was that somatic diseases induced by psychological agents should also be taken into account. In addition, we assumed that certain values corresponding to independent risks substituted by the plant installation should be subtracted from the standard risk values. Since the two effects, psychosomatic and substitutional, seem to be different for various energy systems, they may influence the above risk comparison and ranking.

2.2. Environmental transfer model

The health risk assessments reviewed in Section 2.1 are based on a fundamental risk assessment paradigm, released by the US National Academy of Sciences in 1983 [11]. This paradigm defines the steps of the risk evaluation process for each toxic substance, including hazard identification, exposure and dose-response assessment, and risk characterization.

The consequent generalized environmental transfer pathway comprises various essential components, from sources of emissions in air, water and soil, through concentrations/dispersions and dose-effect relationships, to health and environmental risk (Ref. [4], p. 16).

The related standard structure of a risk management system has two distinctive focal components — assessment and perception [12]. Psychological factors, if considered, are connected only with the risk perception level, without any influence on the assessment of somatic diseases.

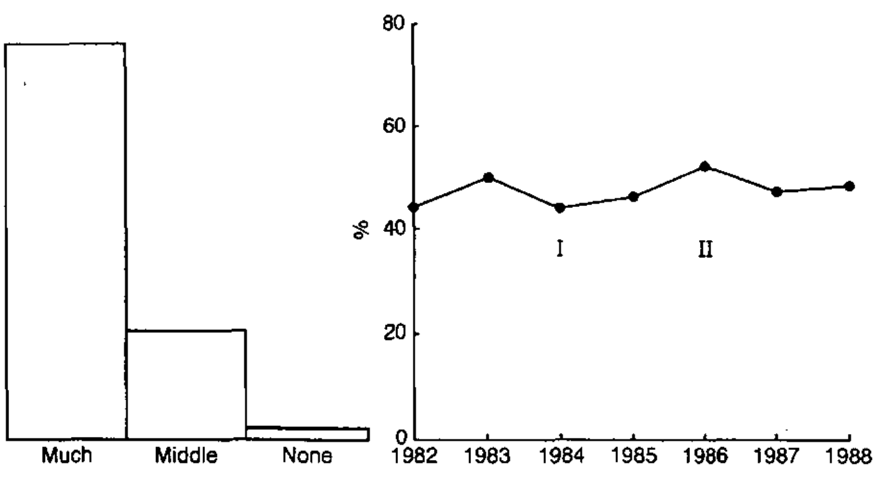
3. PSYCHOSOMATIC EFFECTS

3.1. Psychological pollution

As can be inferred from the previous considerations, the standard health risk assessment procedures implicitly presume the following causality sequence: material (physical, chemical) agent → tissue harm → functional disorder. This model, which can be considered as a classical one, implies that health damages always originate from some material pollutants (toxic substances, radiation, etc.).

However, technological risk sources may also induce other kinds of agents, in addition to the material ones. These can be identified as emotional stresses (fear, anxiety, etc.) leading to chronic activation of the autonomous nervous system (sympatic or parasympatic) and consequently to functional disturbance, resulting in somatic (organic) damage or disease. From these considerations, we have formulated an inverse causality model in risk assessment [13]: immaterial (psychological) agent → functional disorder → tissue harm. The initial idea of this approach within 'riskology' goes back to a three-dimensional representation of technological risks, combining a horizontal psychological plane and a vertical somatic axis [14]. The general result is that, in parallel with emitted physical/chemical pollution, energy and other technological systems may be the sources of 'psychological pollution', with comparable consequences for human health and welfare.

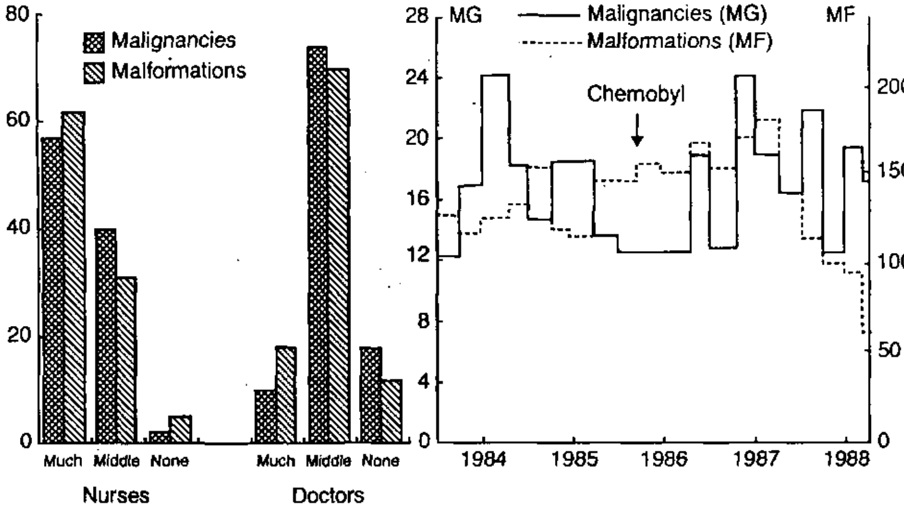
In order to investigate the presence of psychological pollution from energy systems, we performed a comparison of opinions and facts about the health impacts of coal fuelled power plants [15]. The medical staff for health protection near the Bitola power plant was interrogated about their opinions concerning a possible increase in the number of respiratory disorders caused by plant operation (Fig. 2); 77% of the medical doctors and other medical workers said that the number of respiratory diseases had greatly increased during plant operation; only 2% of the staff gave negative answers. Figure 2 shows also the real incidence of respiratory



Opinions of medical staff about the influence of the plant on respiratory diseases

Factual incidence of respiratory diseases before and after the introduction of units I and II

FIG. 2. Psychological and somatic effects of the coal fuelled power plant Bitola.



Opinions of pediatric staff in Skopje concerning the increase of malignancies and malformations of children in this region after the Chernobyl accident

Factual incidence of malignancies and malformations of children in the Skopje region before and after the Chernobyl accident

FIG. 3. Psychological and somatic effects of low doses of nuclear radiation.

disorders evidenced before and after installation of plant units I and II. It is evident that the number of respiratory diseases did not increase. Thus, it can be inferred that pronounced psychological pollution is actually present.

Similar conclusions about psychological pollution can be drawn from a study of opinions about and the factual incidence of malignancies and malformations of children in the southern region of the former Yugoslavia, near the Skopje (approximately five million inhabitants) Pediatric Clinic. A survey of the opinions of the staff from this clinic (89 medical doctors and 50 nurses) was performed in December 1988 [16]. The first question was: "Do you think that in your region the number of malignancies of children has increased after the Chernobyl accident?" The second question was the same, but concerned malformations. The results of this survey are presented in Fig. 3, together with the actual changes in the number of malignancies and malformations of children in the period 1984–1988. Again, the striking discrepancy between opinions and facts illustrates the psychological pollution of people, even of professionals.

3.2. Psychosomatic diseases

As is well known, there are several somatic diseases for which psychological factors have been found in aetiological studies to play an essential role. The primary psychosomatic diseases are peptic ulcer, arterial hypertension, bronchial asthma,

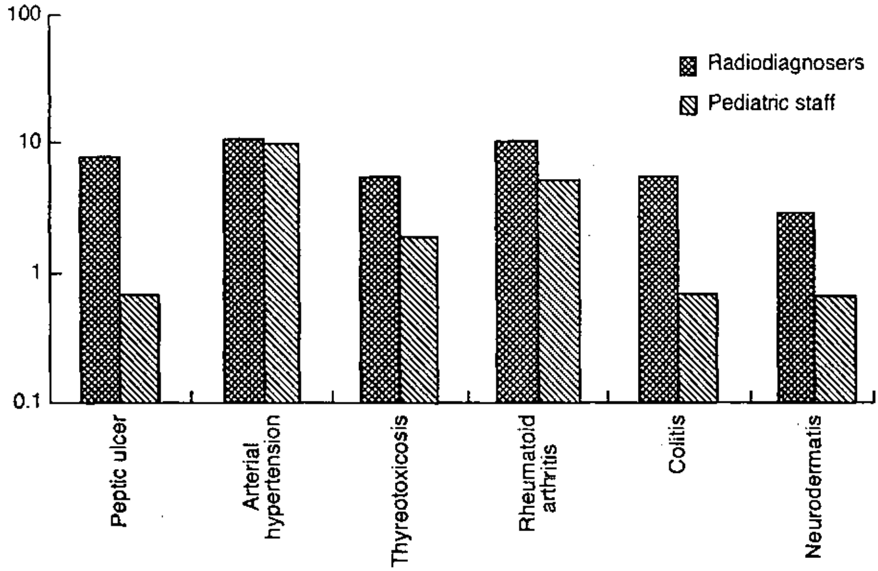


FIG. 4. Incidence of primary psychosomatic diseases due to chronic stress (percentage of the total number of staff in the group).

diseases of the thyreoideae, rheumatic arthritis, colitis and neurodermatitis. For many other diseases the psychological element is only one among several parallel factors; these are known as secondary psychosomatic diseases.

In general, the stressors are being refracted through the individual history of a person as through a prism, leading to a spectrum of possible reactions [17]. The personality prism comprises heredity, early childhood experiences and actual conflicts, while the resulting disorders may be disturbed behaviour on one hand and psychosomatic diseases on the other. The probability of each outcome depends primarily on the individual personality prism, as well as on the characteristics of the stressors.

It is important to note that the main factor provoking psychosomatic diseases is not acute stress but rather chronic stress, which is typical for contemporary technologies. A characteristic example from the Skopje Medical Faculty is shown in Fig. 4.

The standard calculation of the health effects of technological emissions typically involves extrapolating dose-response information from animal or epidemiological studies [18]. This means that the psychosomatic approach, which is an important ingredient of modern medical science, is lacking in the present risk analysis, which is based on the classical model mentioned in Section 2.2.

Some preliminary results on the incidence of psychosomatic diseases at power plants are presented in Figs 5 and 6. Two power plants (each about 630 MW(e)) have been investigated: the coal fuelled power plant at Bitola (The Former Yugoslav Republic of Macedonia) and the PWR nuclear power plant at Krško (Slovenia). The results were compared with two control groups: one group from a district of Skopje in the case of the coal plant and one from Krško village in the case of the nuclear plant. The data were taken from the evidence of the related medical care institution for the year 1994.

From Figs 5 and 6 it can be seen that there is an increase in the relative incidence of practically all psychosomatic diseases. The two most characteristic psychosomatic diseases, peptic ulcer and arterial hypertension, are particularly pronounced. In addition, an increase in the percentage of asthma in the case of the coal plant and an increase in colitis and neurodermatitis in the case of the nuclear power plant were noticed, whose aetiology may not be only stressogene. It is interesting that (in contrast to psychosomatic diseases) no cases of cancer were evidenced for the staff of both plants.

In spite of the preliminary and partial character of the above results (the mining stage was not included), they clearly indicate the presence of psychosomatic occupational risks, justifying more detailed investigations.

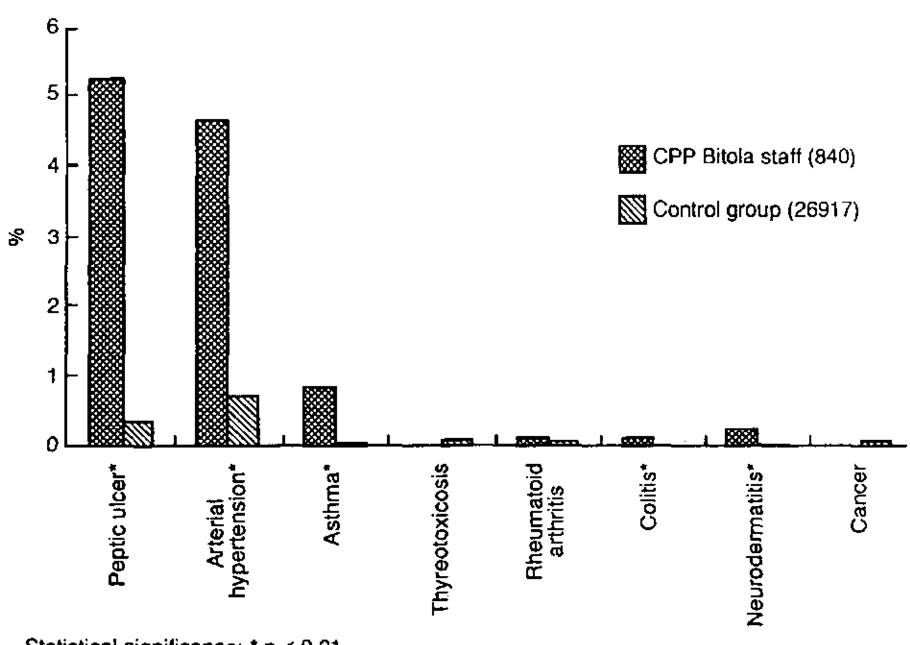


FIG. 5. Incidence of primary psychosomatic diseases and cancer at the coal fuelled power plant Bitola (percentage of the total number of patients in the group).

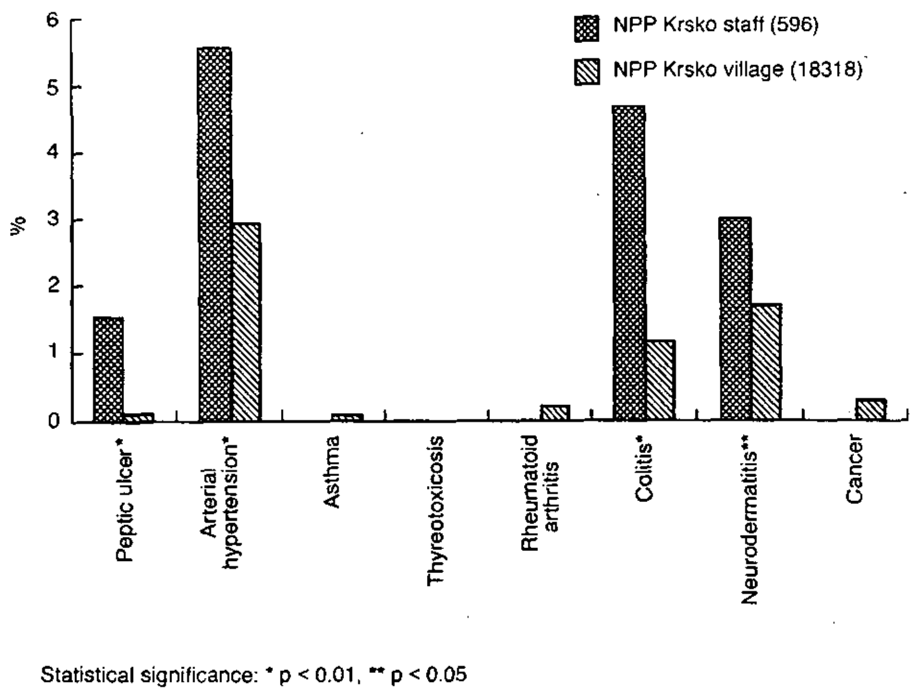


FIG. 6. Incidence of primary psychosomatic disease and cancer at the nuclear power plant Krško (percentage of the total number of patients in the group).

4. SUBSTITUTIONAL EFFECTS

Besides the psychosomatic risk, which tends to increase the total health risk level, an additional effect, which decreases the standard risk values, should be taken into account. This is the effect of 'substituted pollution', by which we denote the risk from replaced materials and other sources of hazards that would be present if no power plant had been built.

A typical illustration of this effect is the integration of a photovoltaic (PV) installation into buildings, where the PV installation substitutes the facade or roof elements. As an example, a SOFREL PV roof installation comprises (per MW) approximately 2000 t of concrete paving stones, 1160 t of concrete bases, 66 t of glass and 20 t of other materials [19]. The risk from a solar plant originates mainly from producing and transporting all this material. However, the same flat roof without a PV installation would be composed of 4000 t of concrete paving stones, and the corresponding risks from this material should be subtracted from the standard values of risk.

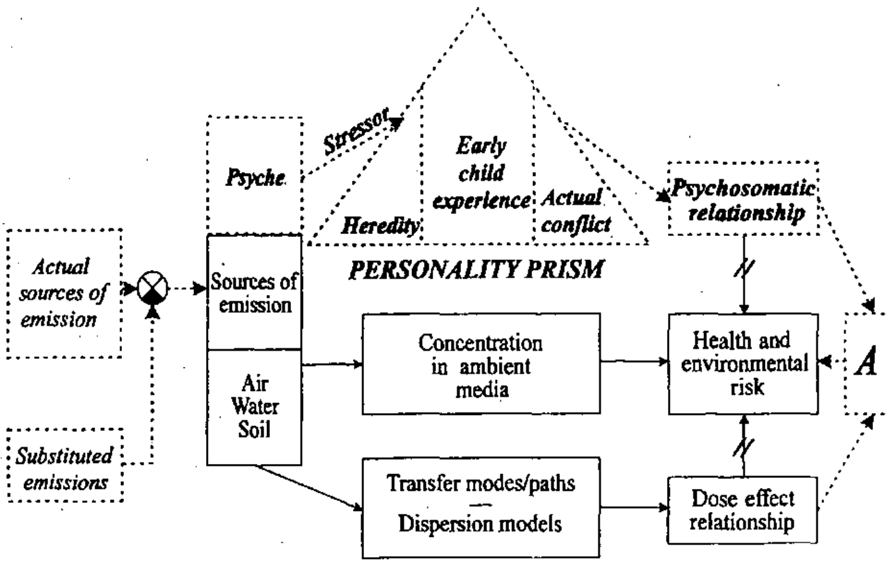


FIG. 7. Modified risk pathway.

The substitutional effects may also be pronounced in the case of nuclear plants. For example, measurements have shown that the doses at the fence of the Krško nuclear power plant were always systematically lower than those at a longer distance, obviously because of the lower radioactivity of the artificially built ground of the plant compared with that of the natural soil [20]. In addition, for technological reasons (low neutron absorption), the output water from a nuclear power plant can be cleaner than the input water (e.g. the water of the Sava River).

Similar corrections of the standard risk values may also be applicable to hydro plants, where the risk of flood from an unregulated river is avoided.

Roughly speaking, the psychosomatic effects tend to increase the total risk from fossil fuelled plants, while the substitutional effects decrease the risk from solar and hydro plants. In the case of nuclear plants, the substitutional effects may partially compensate the psychosomatic ones.

5. CONCLUSION

On the basis of the above considerations of psychosomatic and substitutional effects, the following modifications to the standard approaches concerning health risks from energy systems are suggested:

(a) In the WEC definition of environment [1] (see Footnote 1) the term 'psychological' should be added to 'physical, chemical and biological agents'. In the light of the arguing on psychological pollution, this term is not covered by 'social factors'.

(b) The standard risk transfer pathway (mentioned in Section 2.2) should be modified so as to include the psychosomatic and substitutional components (Fig. 7). The proposed modifications are shown in Fig. 7 by dotted lines; the amplifier on the right hand side and the comparator on the left hand side illustrate the holistic character of the corrections.

(c) The standard risk management scheme (mentioned in Section 2.2) should be supplemented by an additional 'psychosomatic' branch, connecting by feedback the risk perception and risk assessment items.

(d) Electric utilities and decision makers should use specific response measures to diminish the detrimental health effects of psychological pollution: autogene training, interactive communication, multimedia information systems, etc. In addition, integrated and multipurpose power installations should be preferred in order to increase the compensating effects of substituted pollution.

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ASSESSMENT OF HEALTH IMPACTS OF ELECTRICITY GENERATION AND USE

S.C. MORRIS
World Health Organization Collaborating Centre on
Health and Environmental Effects of Energy Systems,
Biomedical and Environmental Assessment Group,
Brookhaven National Laboratory,
Upton, New York, United States of America

Abstract

ASSESSMENT OF HEALTH IMPACTS OF ELECTRICITY GENERATION AND USE.

The paper describes the health effects of concern associated with electricity generation, information from which health effects can be estimated, and how the boundaries of analysis are determined. It also describes advances, new approaches and trends in the risk assessment process. It discusses the application of these advances to comparative risk studies. Trends in the risk assessment process include more explicit characterization of quantitative uncertainty, the broader application and acceptance of Monte Carlo analysis and other numerical methods to the propagation of uncertainties through the analysis, greater realism in risk assessment, and the application of greatly increased computational capabilities.

1. INTRODUCTION

Energy is an important driving force for economic development. In turn, the health of a population is strongly dependent on the wealth generated by that development. Generation of electricity provides the greatest flexibility in the end-use of energy, and availability of electricity is an important *indicator* (not cause) of socioeconomic development and associated health benefits. For some parts of the industrialized world and for many developing countries, this role of energy is of crucial importance for improving the health of the population [1].

Maintaining economic development may remain an issue of first priority, but growing pollution from energy and other sources reduces the benefits. This is clear in major urban centres in the developing world and in eastern European countries where increasing emphasis is being placed on environmental and health concerns. Studies continue to identify sulphur, particulate and oxidant air pollutants as harmful to health [2], while international guidelines provide a basis for safe levels of environmental quality [3]. The climate change issue introduces new demands and new uncertainties in planning for energy system development. The Framework Convention on Climate Change is fostering analyses of energy use in most of the nations of the world. These analyses will take a new look at demand-side management and at new and renewable sources of electricity. Growth in renewable energy sources is fastest in the developing world. This is partly driven by the increasing demand for electricity. Much of this will be small scale development. The chief executive officer of a large engineering firm recently indicated his belief that "Localized energy sources, such as small windmills ... may be vastly preferable to large power-plants with massive far-flung distribution grids" [4].

Electricity is the fastest growing form of end-use energy worldwide. New capacity built in the next 25 years is expected to exceed all capacity built to date. Most of this capacity will be built in Asia, Latin America and Africa [5]. Along with this growth, the electricity sector is changing dramatically around the world. New institutional arrangements and new decision makers are appearing as a result of deregulation, privatization and competition.

The world is facing a period of new investment needs in electrical and other energy technologies, increasing demands for a cleaner environment, and a changing institutional and regulatory milieu. Perhaps more than ever before, utilities, communities and nations need tools to do comparative assessments to support the development of investment decisions and energy and environmental strategies [6].

Numerous studies done in the 1970s and 1980s compared the health effects of different energy systems. Many key papers were consolidated or summarized in symposia [7, 8]. These provided information on and insight into the kind and relative magnitude of effects caused by different energy systems, but they had little impact on investment strategy. Although studies on potential health effects of individual electrical technologies or facilities continued, comparative studies waned during the mid- to late-1980s. More recent emphasis has been placed on integrated community planning at the local level where implementation may be more likely. Examples include the Health and Environmental Analysis for Decision-making — Linkage Analysis and Monitoring Project, of the World Health Organization (see Ref. [9]).

2. STRUCTURING COMPARATIVE HEALTH RISK ANALYSIS

Comparative risk assessment requires a clear and consistent set of assumptions and a definition of the systems to be compared [10]. A key factor is the delineation of the system boundary. The entire fuel cycle, from resource to ultimate useful energy service, must be considered. In some cases, the health impact of the construction and manufacture of the equipment is important. Economic input–output analysis is one approach to capture the total picture, but the degree of aggregation is such that small components that have potentially important health implications, such as cadmium production, are lost in the average effects of broad categories [11]. More recently, system boundary considerations have focused on the life cycle concept, including entire projects, from the preparatory phase to decommissioning [12].

Geographic scale also provides system boundaries. Analysis aimed at decision making must be limited to the boundaries of a decision making entity. Even for environmental problems that demand a regional or global outlook, such as acid rain or climate change, decision making authority is lodged in individual political entities where trade-offs between environmental quality and economic development are made. In these cases, the global picture is needed to characterize the problem, but it must be disaggregated to the local or national level to achieve a solution.

Establishing the boundaries of the analysis for the energy system is only half of the task of structuring the analysis. One must determine the environmental agents to be considered, the environmental pathways by which they reach people, and the range of health impact. These will vary by technology, local environmental conditions, and perhaps population characteristics. A screening analysis may be useful to help decide which can be omitted safely. Pathways include air, surface water, groundwater, food-chains, and direct impacts such as radiation, noise and trauma. Some environmental agents may pass through several pathways to reach people. These all involve environmental modelling. The ultimate link in the chain, however, is how people come into contact with environmental agents. This involves the geographical and time dependent interaction between environmental concentrations and people's activity patterns.

3. HEALTH EFFECTS OF CONCERN

Health effects can be classified as mortality, morbidity, reproductive effects, impairment of function and performance, and other effects on well-being such as irritation or obscuration of sunlight [13]. These effects are qualitatively different and cannot easily be combined in an analysis without losing information.

Effects are usually divided into occupational effects and effects on the general population. Diseases of important concern in energy systems include: cancer, linked to some combustion products, radiation emissions and possibly electromagnetic fields (EMFs) [14]; respiratory disease, linked to coal mining and high levels of air pollution [2, 15]; and malaria, schistosomiasis, onchocerciasis, and parasitic infections linked to hydroelectric projects [16, 17]. More recently, greater attention has been given to health effects that may be more subtle or more difficult to link directly with a source. These include reproductive [18] and neurological [19–21] effects.

The possible health effects of EMFs of 50–60 Hz pose an especially difficult problem. Epidemiological results have been mixed and, although considerable evidence exists of cellular level changes associated with EMFs, convincing evidence of a mechanism has not been found to explain the observed effects. Health risks from EMFs cannot be reliably estimated. The pervasiveness of EMF sources makes this an important issue to resolve, but resolution does not appear to be near [22, 23].

4. INFORMATION NEEDED FOR HEALTH RISK ANALYSIS

Information from a broad range of disciplines must be integrated in order to provide a picture of health risk from energy systems. Available data are seldom complete or sufficient for the needs of a health risk assessment. At the same time, the amount of existing data may be overwhelming. Some examples of the kinds of data required are given below:

— Characteristics of environmental emissions from energy technologies;
— Population density around energy facilities;
— Vulnerability of the population: pre-existing diseases, nutritional status;
— Type of employment in energy generating facilities;
— Level of exposure of workers and the public to toxic agents or risk of injury;
— Characteristics of the dose response relationship;
— Internationalized monitoring of health risk indicators.

Continuing research is needed to increase the understanding of source terms, environmental transport and exposure, and dose response relationships. Atmospheric transport models cannot adequately quantify the incremental contribution of individual power plants to regional pollution, and more effort is needed to quantify the degree of uncertainty involved. The validity of toxicologically based dose response functions for carcinogens has been seriously questioned [24] and epidemiology has not been able to break through the collinearity of multiple pollutants or the effect of uncertainty in exposure estimates.

At the same time, decisions must be made on the basis of current understanding and available data. Efforts have been initiated to make better use of available information by linking different kinds of data in a way to support decision making [9].

5. IMPROVEMENTS AND NEW APPROACHES

Health risk assessment draws on the efforts of a wide range of scientific and technical disciplines. Substantial advances in the methods and techniques available have been made. A major challenge is to incorporate these advances in new comparative assessments. In addition, there has been a substantial change in the underlying approach to risk assessment.

5.1. Exposure assessment

Much greater attention has been given to exposure assessment. Total integrated personal exposure estimates have been based on personal sampling monitors, biomarkers, fixed samplers linked to activity profiles, and exposure models. More accurate exposure assessment improves the development and application of epidemiologically based dose response functions.

5.2. Improved biological understanding

Advances in molecular biology have provided methods to measure biological changes in genes, cells and physiological processes. This allows more accurate measurements of environmental exposure, better determination of individual susceptibility, and improved detection of early health impacts that can better be linked to their causative agents [25]. Dose response aspects of risk assessments are moving towards a stronger biological basis that includes physiologically based pharmacokinetic models and cell kinetics [26]. There has been an explosive growth in air pollution epidemiology in the last few years. This addressed new concerns regarding toxic and exotic compounds as well as a renewed concern with the more familiar particulate pollution.

5.3. Advances associated with computational ability

The wide availability of powerful personal computers, software and on-line databases has made substantial impacts on health risk assessment. Improved computer software for multimedia environmental transport modelling is widely available. Information on individual chemicals is readily available from on-line databases and on CD-ROM.

5.4. Explicit characterization of quantitative uncertainty in health risk analysis

Some early efforts were made to explicitly quantify uncertainties and to propagate them through analyses using numerical techniques such as Monte Carlo analysis [27, 28]. The need to make uncertainties explicit at every stage of the analysis is now generally accepted [29, 30]. Considerable literature is available on this topic [31–34]. Moreover, quantitative evaluation of uncertainty helps to evaluate the probabilities and consequences of making errors in decisions; it is not just another tool to answer questions about relative magnitude [35].

Together with the greater attention to uncertainty came the recognition that uncertainty stems from different causes and that in some cases individual heterogeneity in the population was masquerading as uncertainty. Both heterogeneity and uncertainty are described with probability (or frequency) distributions. When they are dealt with independently, they are treated in much the same way analytically. When they are combined in an analysis, however, a more complex approach, consisting of a two-dimensional Monte Carlo analysis, is necessary [36, 37].

5.5. Scope of health impacts considered

The scope of health impacts that are considered in health risk assessments has expanded. While earlier analyses were often limited to cancer, trauma and respiratory disease, now more subtle effects are often included, such as reproductive and neurological effects. This trend is due partially to a greater recognition of the potential role of these effects and partially to improvements in the understanding of these areas. In addition to expanding the kinds of effects, there is a greater recognition that certain subgroups of the population may be at greater risk and should receive more attention in the analysis. These include people with greater susceptibility as a result of genetic predisposition or prior disease.

5.6. More realistic health risk analysis

A general trend to a more realistic approach to risk assessment has developed. Some attributes of this realistic approach are given below (see Ref. [38]).

Realistic risk assessment:

— Avoids unrealistic and conservative exposure scenarios by focusing on the development of reasonable and sensible scenarios;
— Replaces generic or inappropriate default assumptions with site specific data;
— Explicitly characterizes uncertainties in model parameters rather than relying on conservative assumptions;
— Uses site specific transport and exposure models as well as available measurement data to calibrate models or input parameters;
— Propagates uncertainty properly through the analysis, using analytical or numeric techniques as appropriate;
— Uses the latest mechanistic information and models in describing dose response relationships.

6. LINKAGE BETWEEN COMPARATIVE HEALTH RISK ASSESSMENT AND ENERGY SYSTEM MODELLING

The resurgence of energy system modelling to develop strategies for greenhouse gas reduction combined with modern computing capabilities offers an opportunity to strengthen comparative health risk assessments. Health effect assessments, while sometimes co-ordinated with energy system models, have not been integrated with them. Yet, energy system models include many of the environmental emission terms that form the starting point of effect assessments. One difficulty was the importance of geographic factors in environmental transport. The value of linking an energy system model to environmental transport and effect models using geographic information systems has been demonstrated in Indonesia with the MARKAL model [39]. Substantial work has also been done with MARKAL in local energy emission control planning in Sweden [38].

One difficulty to be addressed is that, while energy system models generally address a single country or region, few countries contain entire fuel cycles within their boundaries. Every country imports or exports some form of energy. Moreover, environmental pollutants from energy systems cross national boundaries. A linkage with energy system models will require apportionment of health risks among countries.

7. CONCLUSIONS

All energy technologies involve some degree of health risk, either in their operation, construction and final disposal, or in some combination of these. Despite limitations, comparative health risk assessment provides decision makers with the basis for incorporating these factors into investment decisions. Significant advances have been made in the practice of health risk assessment, and in the tools and data available for conducting assessment. These advances could be applied in a new effort at comparative health risk assessments of energy systems.

The potential role of comparative health risk analysis in the electric energy sector is worth considering. In 1984, Whipple and Star [40] pointed out that, despite many studies on comparative risks, the relative health effects of different methods of electric power had little effect on the choice of electric power generation. Since then, there have been few studies on comparative risks of different methods of generating electricity. There has, however, been increasing public concern about the environmental and health aspects of the electric power system, in particular air pollution, ionizing radiation, and EMFs associated with transmission and distribution lines. Increasingly strict regulations on air pollution emissions represent, in part, the continuing concern over potential health impacts. There are, of course, many other factors to be considered in the choice of power generation methods and it is necessary to keep the role of health impacts in perspective, recognizing that indirect positive effects of economic development may outweigh the direct negative environmental effects. The level of health impacts may be sufficiently small or subject to mitigation at a cost low enough that relative health impacts are not a major decision factor, and one must be careful in comparative risk analysis not to accentuate small differences among different technologies. Comparative assessments are required to provide information on the relative importance of health effects in decision making.

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EXTERNAL COSTS OF ELECTRICITY
Valuation of health impacts

A. MARKANDYA
Harvard Institute for International Development,
Harvard University,
Cambridge, Massachusetts,
United States of America

Abstract

EXTERNAL COSTS OF ELECTRICITY: VALUATION OF HEALTH IMPACTS.

The health impacts of electricity generation can be significant, depending on the choice of technology and fuel, and the location of the plant. The paper discusses the methodological issues that arise in estimating these impacts in monetary terms. The first part of the paper argues for the use of a willingness to pay approach and discusses some of the problems that arise in implementing the methodology, the most prominent ones being the time-scale of impacts, discounting, uncertainty, and the transferability of data from one location to another. The second part of the paper reviews the literature on the estimation of mortality and morbidity impacts and gives some numbers from a recent study financed by the European Commission. Although there are many problems to be resolved, the monetary valuation of health impacts can assist in the decision making process, both in the selection of fuels and technologies and in the location of plants.

1. INTRODUCTION

The issues arising in the monetary valuation of the health impacts of electricity generation, especially those involving fossil fuels, are discussed in this section, including the basic methodology for valuation and the way of determining its scope. The valuation of health impacts is discussed in Session 2. The methodology was used in the recently completed fuel cycle study [1] and in the study on externalities of fuel cycles (ExternE) [2] by the European Commission, in which the author played a major part.

1.1. Scope of the valuation

The philosophy underlying valuation is based on individual preferences, which are expressed through the willingness to pay (WTP) for something that improves individual welfare and the willingness to accept payment (WTA) for something that reduces individual welfare. The total value of environmental impacts is taken as the sum of the WTP or WTA of the individuals comprising it. Thus, no special weight is given to any particular group. This approach is in contrast to, for example, approaches using values based on expert opinion or values based on the costs of making good any damage to the environment by the fuel cycle.

The WTP/WTA numbers can be expressed for two categories of value, namely *use values* and *non-use values*. Non-use values are also sometimes referred to as *existence values*. In the category of use values there are many different sub-categories. *Direct use values* arise when an individual makes use of the environment (e.g. breathing the air) and suffers a loss of welfare if that environment is polluted. *Indirect use values* arise when the welfare of a person is affected by what happens to another individual. For example, if somebody suffers a loss of welfare as a result of the death or illness of a friend or relative, resulting from increased levels of air pollution, this loss of welfare translates into a cost through the WTP of that person. Indirect use values have been measured in limited cases and are referred to as *altruistic values* (see later in this section for details). Both direct use values and indirect use values have a time dimension; an environmental change today can result in such values now and in the future.

The category of non-use values is a controversial category, although values deriving from the existence of a pristine environment are real enough, even for those who never make use of it. In some respects it is not clear what constitutes 'use' and 'non-use'. Pure non-use values are those which do not involve any welfare from any sensory experience related to the item being valued. The difficulty in defining non-use values is connected with the difficulty of measuring them. The only valuation method available for this category is that of using a questionnaire, or 'contingent valuation method' (CVM). This method has been tested and improved extensively in the past 20 years, and the general consensus is that the technique works effectively when 'market conditions' of exchange can be simulated effectively and when the respondent has considerable familiarity with the item being valued. For most values in the non-use category this is simply not the case. Hence, for the present, non-use values are extremely difficult to value with any accuracy.

Although monetary valuation of environmental impacts is widespread and growing, there are still many people who find the idea strange at best, and distasteful and unacceptable at worst. Given the central role of monetary valuation in the present study, a justification of the method is warranted.

One objection to the use of the WTP is that it is 'income constrained'. The WTP of a poorer person is less than that of a richer person, other things being equal. This is the case particularly in connection with the value of a statistical life (VOSL), where the WTP for avoiding an increase in the risk of death is measured in terms of a VOSL. In general, one would expect the VOSL for a poor person to be lower than that for a rich person. But this is no more or less objectionable than saying that a rich person can and does spend more money on health protection than a poor person or that individuals of higher social status live longer on average than persons of lower status. The basic inequalities in society result in environmental values varying with income. One may object to these inequalities and make a strong case to change them, but, as long as they exist, one has to accept the consequences.

This raises a related issue that arises in the valuation of externalities, namely the spatial range over which the values should be measured. An increase in air emissions at one place in Europe certainly has an impact on all parts of Europe and may also affect other continents. The question is: whose environmental costs should be valued? For most policy purposes it is important to know the costs of *all* groups affected and so the estimation methodology should not respect national or even continental boundaries. However, it is also true that not all costs will have equal relevance to all decisions. With respect to global warming, for example, European Governments will devise an accommodation or protection strategy that is based on the likely costs in Europe. Hence, these costs should be calculated separately from the costs to other regions of the world. Furthermore, some costs are difficult to assess. For example, if a European power station uses imported South African coal or imported Nigerian oil, the question is how much of the external costs for mining, drilling, etc., should be included. In principle, costs of fuel from countries outside the European Union (EU) could be relevant to some decisions (e.g. EU importation policy), but possibly not to others (e.g. environmental charges imposed on private electricity generators in Europe).

1.2. Technologies

Energy supply technologies have an operating lifetime of many years, and there will be environmental consequences over an even longer period. The basic question is, what impacts are to be quantified: those of running the plant for a limited period, such as a year, or those of running the plant for its lifetime. Estimating the impact over a specified period such as a year has the advantage that it is possible to trace the effects more fully; also, the 'reference environment' is more easily defined. It should be noted that analysing the impact of operating a plant for one year does not imply that the environmental and health impacts will also be evaluated for that period, since these will be effective for a longer period of time and it would be incorrect to restrict oneself to the same time horizon over which the operation is being measured. For example, a nuclear power plant may have a lifetime of 30 years. However, even regarding the impacts of low level normal radiation, a period of over 130 years must be allowed for, so that the health risks of infants born in the last year of operation of the plant can be traced over the normal expected lifetime of these infants.

The disadvantage of looking at a limited period is that some of the environmental impacts arise at the beginning and some arise at the end of the operating life of the plant (e.g. construction and decommissioning). Allowing for these impacts would be difficult in the context of a one year operating framework. The policy relevant question that needs to be answered is what social cost the application of a technology imposes on society. In order to answer that question, it is necessary to look at the operations over the lifetime of the plant. It may also be desirable to know the external costs associated with construction and decommissioning, separately from the costs of operation. If these external cost were known, it would be possible to impose an 'environmental charge' on the different groups responsible for the different operating stages. However, this also requires carrying out a lifetime analysis.

1.3. Impacts and damages

The impacts of a particular operation (e.g. noise and odour) may last for a period that is as short as the operating period itself, whereas the impacts of other operations (e.g. recovery of acidified soil and disposal of radioactive waste) may last for hundreds or even thousands of years. In principle, each impact should be traced for as long as it is considered to be relevant to human welfare. No arbitrary limit should be imposed, such as stipulating that when X% of the potential damages is assessed, the analysis will be terminated. In practice, this assessment can be limited by: (a) uncertainty about the physical impacts in the distant future and (b) difficulty in defining a reference environment.

The methodology for evaluating impacts and damages is based on taking the difference between the environmental situation without the operation under consideration and the environmental situation with it. However, the difficulties in defining the 'without operation' case (i.e. the reference environment) are very large. The relevant variables in describing the reference environment include background levels of emissions and other environmental characteristics, as well as socio-economic variables such as age and composition of the population at risk. Beyond a period of about 20 years, it is virtually impossible to make such projections with any certainty. Although it is not possible to assume in all cases that the "economic conditions will remain as they are now", this is often the only practicable assumption that can be made.

1.4. Discount rates

Discounting is the practice of placing lower numerical values on future benefits and costs than on present benefits and costs. In the valuation of environmental impacts of electricity generation, discounting is an important issue because many of the environmental damages of present actions will occur many years from now and, the higher the discount rate, the lower the value that will be attached to these damages. This can have major implications for a policy.

One criticism of discounting in connection with environmental issues relates to compensation across generations. Suppose a present operation would cause an environmental damage of X ECU, T years from now. The argument for representing this damage in discounted terms by the amount X ECU/(i + r)^T is the following. If the latter amount were invested at the opportunity cost of the capital discount rate r, it would amount to X ECU in T years' time. This could then be used to compensate those who suffer the damage in those years. Parfitt [3] argues, however, that using the discounted value is only legitimate if the compensation is *actually* paid; otherwise, this damage cannot be represented by a discounted cost.

Although Parfitt's position is not entirely correct, it raises some very real issues. In some cases the investment fund needs to be held for very long periods before the potential compensation becomes due. With some forms of nuclear waste the period could be thousands of years. Human experience with capital investments and their rates of return does not cover more than a couple of hundred years at the most. To give an example, if 1 ECU were invested today at a real rate of return of 7% per annum, it would amount to nearly 491 trillion ECU in 500 years' time. Such amounts are inconceivable and it is not reasonable to base decisions regarding the protection of future generations on them. In the ExternE project it became soon evident that, if damages occur in the very distant future, the use of discount rates is not a reasonable way of dealing with them. At any positive discount rate the costs become insignificant, and at a zero rate they are so large as to dominate all calculations. One possible solution is to define the rights of future generations and to use those rights to circumscribe the options in terms of what impacts can be imposed on future generations.

1.5. Uncertainty

Uncertainty in its various manifestations is arguably the most important and the least satisfactorily addressed aspect of the whole assessment of the environmental impacts of fuel cycles (not just the economic component). There are two distinct aspects of uncertainty: (1) the uncertainty about the different parameters of the impact pathway, including the monetary valuation, and (2) the impact of uncertainty on the valuation of impacts, such as accidents and risks of diseases. In the ExternE study it was noted that overall uncertainty is the product of uncertainty in each of the four stages of the impact pathway: estimation of emissions, calculation of the spatial dispersion of the emissions, estimation of the physical impact of the dispersed pollutants, and valuation of these impacts. If one could quantify the uncertainty at each of these stages, one could quantify the overall uncertainty in terms of some probability distribution. However, it is not generally possible to quantify the uncertainty in terms of probability distributions. A French application of the ExternE methodology concerned a special case where the underlying distribution was assumed to be lognormal and some subjective estimates of the geometric standard deviation of that distribution were made. In that special case it was possible to arrive at confidence intervals for the damage estimates [4].

Unfortunately, this model cannot always be applied, and hence the standard treatment of uncertainty in the present study has been to take a scenario approach. A 'base case' value for each key parameter is combined with values for low and high case scenarios. As a rough guide, the high case scenarios could use estimates of parameters that are 100% higher than those of the base case, and the low case scenarios could use values that are 50% higher than those of the base case. This does not provide a statistically valid estimate of the range of values for the external costs, with a given confidence interval; it also does not resolve the uncertainty issue, but it will be a useful indication of where the uncertainties lie.

1.6. Transferability of estimates of environmental damage

The environmental damage associated with a particular fuel cycle will depend on the type of plant being considered and on the time when that plant is operating. However, it would clearly not be feasible to estimate all environmental damages for each location and for each time specific fuel cycle ab initio. Much of the work required is extremely time consuming and expensive, making the transfer of estimates from one study to another an important part of the exercise. The difficulty is to know when an estimate of damage is transferable and what modifications, if any, need to be made before it can be used in the new context.

Benefit transfer is "an application of monetary values from a particular valuation study to an alternative or secondary policy decision setting, often in another geographic area than the one where the original study was performed" [5]. Three main biases are inherent in transferring benefits from one area to other areas:

(a) The original data sets vary from those valid at the place of application, and the problems inherent in non-market valuation methods are magnified if they are transferred to another area.

(b) Monetary estimates are often given in units other than those used for expressing the impacts. For example, mortality is estimated by dose response functions (reduced fish populations), while benefit estimates are based on behavioural changes (reduced number of fishing days). The linkage between these two units must be established to enable damage estimation.

(c) Benefits are most often estimated in average, non-marginal terms and studies do not use methods that are designed to be transferable in terms of site, region and population characteristics.

Application of benefit transfer can be based on expert opinion or meta-analysis. Expert opinion concerns the reasonableness involved in making the transfer and in determining what modifications or proxies are needed to make the transfer more accurate. In the ExternE study, expert opinion was often resorted to in making a benefit transfer. In general, the more 'conditional' the original data estimates (e.g. damages *per person, per unit of dispersed pollution, for a given age distribution*), the better the benefit transfer will be.

If there are several studies that give similar final estimates of environmental damage and if there are significant differences between these studies in terms of background variables, a procedure known as *meta-analysis* can be used to transfer the results from one study to other applications. Meta-analysis is a process in which the estimated damages from a range of studies of, for example, coal fired plants are varied systematically, according to the affected population, building areas, crops, level of income of the population, etc. Econometric techniques are used which yield estimates of the responsiveness of damages to the various factors that render them more transferable across situations. These estimates can then be used to derive a simple formula relating environmental costs to per capita income, which could be employed to calculate damages in countries where no relevant studies are available.

Estimates of damages based on meta-analysis have been provided in a formal sense in a study on air pollution carried out in the United States of America [6]. A formal meta-analysis is difficult to carry out and has proved not to be possible in the ExternE study. However, some of the 'expert' adjustments do use an informal meta-analysis. For example, when estimates of damages to the size of a population are adjusted in order to obtain a per capita estimate and when this estimate is transferred to a new study, then it is implicitly assumed that the damages are proportional to the population.

2. VALUATION OF SPECIFIC HEALTH IMPACTS

The valuation of health impacts can be divided into mortality impacts and morbidity impacts, and into occupational health impacts and public health impacts. This section reviews the literature regarding these different impacts, but it does not comment on the dose response functions used, except in so far as this is relevant to the valuation procedures.

2.1. Mortality impacts

The mortality approach in the valuation literature is based on the estimation of the WTP for a change in the risk of death. This is converted to the VOSL by dividing the WTP by the change in risk. Thus, for example, if the estimated WTP is 100 ECU for a reduction in the risk of death of 1/10 000, the VOSL is estimated at 100 × 10 000, i.e. one million ECU.

Estimates of the WTP for a reduction in risk or of the WTA for an increase in risk have been made by three methods. First, there are studies on the increased compensation of individuals who work in occupations where the risk of death at work is higher (other circumstances being the same as in other occupations). This provides an estimate of the WTA. Second, there are studies based on CVM where individuals are questioned about their WTP and WTA regarding measures that reduce the risk of death from certain activities (e.g. driving); or their WTA regarding measures that, conceivably, increase this risk (e.g. increased road traffic in a given area). Third, researchers have looked at actual voluntary expenditures for items that reduce the risk of death from certain activities, for example the purchase of air bags for cars.

Several surveys of VOSL studies are available in the literature (see Ref. [2] for details). On average, the highest values come from the CVM studies and the lowest values from the consumer market studies where actual expenditures are involved. Excluding extreme or unreliable studies, the range of values obtained is 2.0–2.6 million ECU for the US studies, and 2.5–4.4 million ECU for the European studies. The main issues that arise with the application of the VOSL in the fuel cycle studies are the following[1]:

— The validity of methods used in estimating the VOSL;
— The distinction between voluntary risk and involuntary risk;
— Acute versus chronic mortality and, more generally, age dependent mortality;
— The transfer of risk estimates from different probability ranges.

2.1.1. *Validity of methods of estimating the VOSL*

All three methods of valuing a statistical life have been subject to considerable criticism. The wage-risk method relies on the assumption that there is enough labour mobility to permit individuals to choose their occupations to reflect all their preferences, one of which is the preference for a level of risk. In economies suffering from long standing structural imbalances in the labour markets this is at best a questionable assumption. It is difficult to distinguish between risks of mortality and risks of morbidity. The WTA will depend on perceived probabilities of death. Almost all studies, however, use a measure of the long-run frequency of death as a measure of risk. This makes the results quoted unsatisfactory. The probabilities for which the risks are measured are generally higher than the actual risks for most of the fuel cycle impacts (see below). A related factor is that the high risk occupations involve individuals whose WTA for an increase in the risk of death is not typical of

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[1] A number of the issues discussed under mortality also apply to the case of morbidity, particularly the question of voluntary risk versus involuntary risk and the transfer of risk estimates. To avoid repetition, these issues are not raised again when discussing morbidity. Likewise, the issue of altruistic costs, i.e. the costs of the event to third parties, is discussed under morbidity. This issue is also relevant to the case of mortality, although no satisfactory estimates of such costs exist.

the population at large (e.g. steeplejacks)[2]. The net impact of all these factors is difficult to gauge, but it is *likely* that the estimated WTA will be lower than the true value.

The CVM is subject to the criticism that the possible options are hypothetical and that individuals are not familiar with the concepts of risk involved. Certainly, there have been serious difficulties in conveying the impact of different probability changes through questionnaire methods. Some recent work was undertaken in France on the VOSL question using a CVM [7]. The total WTP was found to level off as the number of lives saved increased from 50 to 5000, implying a strong decrease of value per life saved (by a factor of more than 20 over this range). This raises serious questions about the interpretation of CVMs in this area. The range of values was, however, not inconsistent with the range of the EU figures given above.

Finally, the consumer expenditure approach is subject to the difficulties that perceived probabilities are very different from objective probabilities and that the effects of the expenditures are to reduce the risk of death and the risk of illness following an accident. It is difficult to separate the two impacts in the studies.

For all of these reasons the studies are likely to be biased, with the wage–risk studies producing values that are too low and the CVM studies producing values that are too high. Using an average, as has been done here, is using an average of unknown errors, and one cannot say what the final impact will be. However, these studies are all that is available, and one can draw some comfort from the fact that the values are, in general terms, in a plausible range.

2.1.2. *Voluntary risk and involuntary risk*

There is strong evidence suggesting that individuals treat voluntary risk and involuntary risk differently, with the WTA for voluntary risk being much lower than the WTA for involuntary risk. Starr [8] estimated, on a judgemental basis, the difference between the willingness to accept a voluntary increase in risk and the willingness to accept an involuntary increase in risk. He finds that the latter is around ten times as high as the former for probabilities of death in the range of 10^{-6} to 10^{-7}. Interestingly, for lower probabilities, which are typical of the fuel cycles, estimates of the differences are not available. In another study [9] it is argued that the difference could be as much as 100 times.

This issue is of great importance to some fuel cycle studies, for example where public opposition to nuclear fuel is not reflected in the costs as estimated by using

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[2] This is probably why the VOSL decreases as the mean risk level in a group increases. From a theoretical perspective, one would expect the opposite if the populations were homogeneous. Reference [1] gives data which show that the VOSL more than doubles if one allows for self-selection in the wage–risk studies.

a value of life of around 2.6 million ECU. This may be an issue of perceived lay probabilities versus expert probabilities, but that can only be a partial explanation. At this stage, there is no alternative to using about 2.6 million ECU as the statistical value of life. However, as part of the ongoing research, the issue of voluntary risk should be addressed and a revised estimate of the value of life obtained.

2.1.3. *Acute versus chronic mortality and age dependent mortality*

The problem of age dependent mortality needs to be addressed. One would expect the VOSL to depend on the age of persons, with the life of very old people having a lower value than that of younger persons. Le Net [7] found that the VOSL was highest for an age of about 20 years and then decreased with the age of the person. However, this study does not yield a quantitative measure of this effect because the question asked about age involved ranking only. Since the studies cited above estimate the WTP or WTA for individuals in a narrow age band (often people in the prime of their lives), this may well be a source of bias. Furthermore, these studies refer to sudden death, not death with a latency period. One would expect variations in the WTA according to such differences, with a lower WTA for a possible death at a later time and a higher WTA for an earlier death. However, no acceptable estimates of differences are available.

2.1.4. *Transfer of risk estimates from different probability ranges*

Finally, there is the issue of the probability range over which the estimation is carried out and to which it is applied. Typically, the probabilities of death from the fuel cycle are very low (of the order of 10^{-6} and lower), whereas for the estimated VOSL the probabilities of death are between 10^{-1} and 10^{-5}. Furthermore, as pointed out in Ref. [10], the results from studies at the higher end of the probability range are less reliable. As mentioned earlier, theoretical models tend to predict that the WTA for lower risks should be lower, but the empirical literature shows the opposite. This is partly due to the fact that the groups studied are not homogeneous. The issue remains unresolved and there is little that can be done about this problem at this stage.

2.1.5. *Conclusions*

This survey shows that, although there are many issues to be resolved in valuing mortality impacts, at the present time a figure of 2.6 million ECU for the VOSL in 1990 prices appears to be the best central estimate. A range of problems that need to be addressed in the future was identified. Furthermore, in the absence of any strong evidence against it, the decision was taken to use for both occupational mortality impacts and public mortality impacts, in the fossil fuel cycle and the nuclear fuel cycle, the same estimate of 2.6 million ECU. A further issue that arose in the study was whether to take the same VOSL for all countries or to adjust it according to income/living standards, etc.

2.2. Morbidity impacts

There is an enormous amount of literature on valuing morbidity effects in the USA and a virtual absence of such literature in Europe. The dose response functions for morbidity in the epidemiological literature vary from relating 'end-points' such as days of work lost or cases of cancer to end-points that are based on changes in the lung function, as measured in laboratory conditions. Since the latter are not susceptible to economic valuation, they have not been used.

Valuation is ideally based on the WTP, which should encompass the costs of illness borne by the individual plus any foregone earnings. In addition, any social costs of illness should be covered. The WTP for an illness is thus composed of the following parts: the direct cost of the illness (COI), the value of the time lost because of the illness, the value of the utility lost because of the pain and suffering, and the costs of any expenditures for averting and/or mitigating the effects of the illness. The last category includes both the expenditures for prophylactic measures and the expenditures for the treatment of the illness once it has occurred.

The COI is the easiest to measure, on the basis of the actual expenditures associated with different illnesses. The cost of lost time is typically valued at the post-tax wage rate (for the work time lost) and at the opportunity cost of leisure (for the leisure time lost). The latter is between one half and one third of the post-tax wage. The COI is, of course, only a component of the total cost. However, since the other cost components are difficult to measure, estimates have been made of the ratio between the total WTP and the COI. Recent studies (see Ref. [1]) have come up with estimates of 2.0 for asthma and around 3.0 for a range of other illnesses.

The CVM is the only approach that can estimate the value of pain and suffering. The difficulties are those generally associated with the use of the CVM. In addition, it is difficult to know which of the many costs are included in the responses to the questionnaires. In general, respondents will not include those costs due to illness that are not borne by them (e.g. costs covered by medical insurance); such costs need to be added. The cost in terms of pain and suffering that the illness causes to other people (the so-called altruistic cost) should also be included in this category.

Avertive behaviour is the most complex function to model. It involves the estimation of a health production function that would enable estimating the inputs used by the individual in different health states; taking the difference in value between these, it would be possible to obtain the cost of moving from one health state to another. The difficulty is in estimating that function, where many 'inputs' provide more than one service (e.g. bottled water, air conditioners) and where the changes in consumption as a function of the state of illness are difficult to estimate.

The US fuel cycle study provides an extensive list of the empirical literature on the costs of morbidity. The groups under which the estimates can be classified are discussed below and are summarized in Table I.

TABLE I. VALUATION OF MORBIDITY END-POINTS IN THE ExternE STUDY

End-point	Value (ECU)	Source	Used in
Restricted activity days	62	US studies	PM_{10}
Chronic illness (value of a statistical life)	1 million	US figures adjusted for EU/US differences	Not used
Symptom days	6.3	US studies	PM_{10}
Altruistic impacts	0.4–0.5 of private cost	UK studies[a]	Not used
Chest discomfort day	6.3	US studies	SO_2
Emergency room visit	187	US studies	SO_2 and PM_{10}
Respiratory hospital admission	6600	US studies	PM_{10}
Case of bronchitis (child)	138[b]	US studies	PM_{10}
Asthma attack	31[b]	US studies	PM_{10}
Non-fatal cancer	0.25 million	US COI plus foregone earnings	Nuclear fuel cycle
Severe hereditary effect	2.6 million	ExternE study, based on seriousness of public perception	Nuclear fuel cycle
Occupational injuries (minor)	65	French compensation payments	Nuclear fuel cycle
Occupational injuries (permanent disability)	19 000	French compensation payments	Nuclear fuel cycle
Accidents to workers and the public (minor)	420–3400	UK Department of Transport	Coal fuel cycle
Accidents to workers and the public (serious)	20 000 to 200 000	UK Department of Transport	Coal fuel cycle

[a] Studies need further collaboration.

[b] These estimates are being checked by studies in France.

2.2.1. Restricted activity days (RADs)

A large number of studies, using COI as well as CVM, have been used to estimate several categories of RAD. These are differentiated by illness (respiratory RAD or RRAD, angina RAD, etc.) and by severity of impact (minor RAD (MRAD) versus 'normal' RAD). These are among the easier of the health impacts to value, since they relate to acute events lasting a well defined period. *The central estimate obtained for RADs in Europe by this method was 62 ECU.*[3]

2.2.2. Chronic illness

Valuation of chronic illness is largely expressed in terms of the COI approach (although there are a few CVM studies). The COI approach includes direct and indirect costs of the illness (such as lost earnings and loss of leisure time). The CVM approach uses terms similar to the VOSL, obtained by asking what would be the WTP for a reduction of the risk of contracting a chronic respiratory illness. The corresponding value is referred to as the 'value of a statistical case' (or VSC), the best estimate of which is US $1 million (0.8 million ECU, 1990).

2.2.3. Symptom days

There is an extensive literature on the valuation of symptom days, including CVM studies, as well as some studies that combine avertive behaviour and CVM. Although the work carried out is impressive, there are still many difficulties to be resolved. Problems connected with CVM studies are low rates of response to questionnaires and extreme bids that have to be discounted. It is also difficult to know the extent to which the responses include the use of avertive measures. Some of the results appear to indicate that the latter are not always allowed for.

2.2.4. Altruistic impacts

As with symptom days, the existing estimates of the impact of an illness on the utility of other persons are not sufficiently developed for use in a valuation

[3] The US study points out that the central values provided for an RAD cannot be simply multiplied by the number of days lost, because one would expect that the value of each additional day declines as more days are lost; indeed, the empirical evidence supports the assumption that the average value declines as the number of days lost increases. It is probably correct to conclude that the estimated rate of decline in the value of an RAD with the number of days is too inaccurate to be of use, making the use of a single value the best course to follow at this stage.

exercise. One US study [11] came up with an altruistic value for each case of poisoning avoided of more than five times the private valuation. The experiment consisted of a CVM in which individuals were asked about their WTP for a television campaign that would reduce poisoning resulting from poor handling of insecticides. However, the study had a relatively unsophisticated design and the results need to be confirmed by other studies. Work in the United Kingdom [12] suggested that the altruistic values are around 40–50% of the private total valuations. Again, however, these are isolated findings and need to be corroborated. In view of the current state of the art in this area it was decided that altruistic valuations should not be included in the ExternE study.

2.2.5. *Other end-points*[4]

The following other end-points have been valued in the ExternE and US studies, and are summarized in Table I: chest discomfort, emergency room visits, respiratory hospital admissions, children's bronchitis, asthma attacks, non-fatal cancers, severe hereditary effects and occupational impacts. For the last category it was agreed that the VOSL of 2.6 million ECU could be used for mortality impacts, but that for occupational morbidity impacts the WTP estimates discussed above were inappropriate. The illnesses suffered are rather specific and, in so far as miners and other workers suffer from the effects of the end-points defined above, they are included as part of the general public. Hence their valuation is based on the compensation payable to those who suffer from the related diseases, as well as on some other ad hoc assumptions. In particular, the following valuations have been used: nuclear fuel cycle: occupational injuries, 65 ECU, based on compensation payments in France; nuclear fuel cycle: permanent disability, 19 000 ECU, based on compensation payments in France; coal fuel cycle: workers' diseases (simple pneumoconiosis), not valued, since the probability of death is not estimated; coal fuel cycle: accidents: minor injuries, 420–3400 ECU; serious injuries, 20 000 to 200 000 ECU. The figures for accidents are based on estimates of the UK Department of Transport (lower end) and on the speculative estimate for serious injury at the upper end given in Ref. [13].

3. CONCLUSIONS ON HEALTH IMPACT VALUATION

The main conclusions of the morbidity valuation are summarized in Table I. Valuation of morbidity and mortality end-points is a key part of any external cost study of electricity generation. As several such studies show, a major part of the

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[4] Dose response functions relating morbidity end-points to ozone concentrations have not been included here.

external costs arise because of the health impacts. At the same time, there are significant gaps in the values available and for almost all impacts further work is needed. Some work on the valuation side (particularly on the morbidity questions) is being continued by country teams studying the fuel cycle. The initial estimates were based on an extensive review of the literature and a heavy reliance on US morbidity studies. The transferability of these latter estimates is questionable and should certainly be validated. The French implementation team, for example, is doing such work; it is coming up with some estimates that differ from the US ones, but, so far, the differences are not large. For occupational impacts it was decided to use the VOSL for mortality effects, but to rely on compensation data and other COI values for the special morbidity impacts faced by fuel cycle workers. Finally, it should be noted that further work is needed on altruistic impacts as well as on the VOSL for the kinds of impact found in the fuel cycles.

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INTEGRATED FRAMEWORKS FOR COMPARATIVE ASSESSMENT

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INTEGRATING ENERGY AND ENVIRONMENT
Analytical framework and applications

M. MUNASINGHE
University of Colombo,
Colombo, Sri Lanka

Abstract

INTEGRATING ENERGY AND ENVIRONMENT: ANALYTICAL FRAMEWORK AND APPLICATIONS.

The provision of adequate energy supplies has become imperative in the context of the rapidly increasing energy needs of both developing and industrialized countries. In particular, the worldwide demand for electricity has been increasing at a rate higher than the growth rates of both the world economy and the global commercial energy consumption. Thus, there is rising concern about the environmental impact of energy generation in the context of sustainable development. While the problems of the electricity sector in the developing world differ among regions and countries, and while environmental priorities differ between the industrialized and the developing world, it is clear that the expected growth of electricity generation will present a variety of common problems. For example, energy planning in the past was designed primarily to meet demand at least economic cost. By contrast, the pursuit of sustainable energy options requires policy makers to take into account three major aspects of sustainable development: economic, social and environmental.Consequently, there is a need for a comprehensive and integrated conceptual framework for analysis and decision making that will enable policy makers to identify options which lead to improvements in all relevant indices of sustainable development whenever possible, and to make trade-offs among them where necessary. The incorporation of issues such as environmental externalities into decision making is crucial and needs to be addressed at the early sectoral and regional planning stages rather than only at the later stage of environmental assessment of a project. However, this can be extremely problematic. Typically, the application of project level environmental aluation techniques at the power system planning level is extremely difficult owing to intricacies in the valuation of certain social and ecological impacts. In addition, the valuation techniques used, such as contingent valuation, are more appropriate at the micro-level and less effective in situations dealing with a potentially large number of technology, site and mitigation options. Consequently, it is necessary to use multicriteria analysis (MCA), given its central focus of quantification, display and resolution of trade-offs in situations where economic valuation is difficult. Use of MCA, as opposed to cost-benefit analysis, offers policy makers an alternative when progress made towards multiple planning objectives cannot be measured in terms of a single criterion such as monetary value. A practical case study involving MCA is used to demonstrate successfully how environmental considerations may be incorporated into power system planning in Sri Lanka. Finally, it is becoming evident that dealing with energy related environmental and social issues, especially at the global level, will require more co-operation between industrialized and developing countries. Given the resource constraints of developing countries, enhanced financial and technological resource flows from the industrialized world are crucial if the prospects for sustainable energy development are to be realized on a global scale.

1. ENERGY AND ENVIRONMENT: THE CURRENT STATUS

At present, the state of the environment is a major worldwide concern. Pollution in particular is perceived as a serious threat in industrialized countries, where the quality of life had hitherto been measured mainly in terms of growth in material output. Meanwhile, environmental degradation has become a serious impediment to economic development and to the alleviation of poverty in developing countries.

Among the human activities that cause changes in the environment, those associated with the energy sector have a great impact. Energy production, conversion, transportation and utilization have been and continue to be a primary source of local, transnational and global pollution; the environmental effects are: groundwater and air contamination; land degradation and changes in its use; pollution of marine and coastal regions; destruction of ecosystems and loss of biodiversity; damage to health, man-made structures and natural systems from SO_2 and NO_x and from ash particulates, which have a detrimental impact on air quality; and, finally, greenhouse gas emissions, which may have long term impacts on the global environment.

Despite such problems, however, energy services, such as heating, refrigeration, cooking, lighting, communications, motive power and electricity, are essential for economic growth and human well-being. At present, 77% of the world's population live in developing countries, but utilize only a quarter of the world's energy. However, the demand for energy has been growing rapidly in these countries. In the last decade, the rate of growth of energy consumption in the developing countries was almost six times that of the OECD countries and twice that of the average world growth rate.

The rapid growth in energy demand in developing countries (driven primarily by economic expansion, population growth, urbanization, the increasing market penetration of energy using appliances and the transition from traditional energy sources to commercial sources) has surpassed the growth in energy production and power generation capacities, thus creating shortages in primary fuels, electricity and, as a result, financial resources. In addition to the economic burden, environmental degradation associated with an expanding energy sector compound the energy related problems in developing countries.

The crucial dilemma for the developing world is how to reconcile development goals and the elimination of poverty, which will require increased use of energy and raw materials, with responsible stewardship of the environment. This has to be done without overburdening the already weak economies of developing countries. The International Energy Agency (IEA) made a forecast that, through the year 2010, the worldwide use of energy will grow at an annual rate of 2.1% and that the use of energy in East Asian countries will grow at an annual rate of more than 4% [1].

2. IMPORTANCE OF THE ELECTRICITY SECTOR

Electricity is clean, versatile, easily accessible and simple to distribute. Also, it is essential for maintaining a reasonable quality of life and for sustainable development. Because of this, electricity has a larger share of energy in final use and the demand for it is increasing worldwide at almost twice the rate of demand for primary energy. Currently, the worldwide electricity demand is increasing at a rate of over 3.6% annually, which is slightly higher than the world's economic growth rate, twice the population growth rate and more than 1.5 times the growth rate of global commercial energy consumption. At present, 36% of the total energy demand is needed for fuels for electricity generation; in the next 30–40 years, more than half the world's primary commercial energy sources will be utilized for electricity production.

Of the various forms of energy, electricity is particularly important for the developing world. The provision of electricity greatly enhances the quality of life in these countries, particularly that of poor people. About 70% of the population in developing countries live in rural areas. These areas suffer from a lack of essential social and economic infrastructures in connection with education, roads, telecommunication, health, long distance from major commercial and administrative centres, and lack of job opportunities. Thus, remote rural areas are generally inhabited by the poor. Provision of electricity to the poor people in rural areas will improve health standards and assist in education and in motivating people. Rural electrification also helps retard migration from rural areas to cities and enhances opportunities for income generation and employment in rural areas. To the extent that it replaces less efficient and more environmentally damaging fuels, electricity is essential for sustainable development. Hence, given the vital role electricity plays in the development process, the future prospects for economic growth are closely linked to the provision of adequate and reliable electricity supplies. Electricity demand in developing countries has grown very rapidly over the past three decades, with electricity consumption increasing more than 13 fold since 1960.

Such growth rates indicate the need for large additions in capacity. The requirements in Asian regions dominate, with almost two-thirds of the total; coal and hydro are the primary resources, both of which pose specific environmental problems associated with their use [2].

2.1. Electricity, environment and regional concerns

Although the use of electricity is relatively benign, its generation is one of the world's major environmentally damaging activities. While the energy sector contributes 49% of greenhouse gases, electricity generation alone produces more than 25% of energy related carbon dioxide emissions. During the past 20 years, half of all increases in energy related carbon dioxide emissions were from electricity [3].

TABLE I. CO_2 EMISSIONS FROM ENERGY USE (million tonnes)

Year	World	OECD	CEE	DCs	Percentage of coal
1971	4380	2427			
1980	5500	2750	1570	1180	37%
1985	5800	2640	1700	1460	
1990	6550	2900	1700	1950	39%

Source: Khatib and Munasinghe [4].

Most of the growth in worldwide carbon dioxide emissions from 1971 to 1990 is due to the central and eastern European (CEE) countries and the developing countries (Table I).

Despite the use of alternative energy sources, such as wind energy, solar energy and biomass, the largest segment of new electricity in the world is projected to come from coal firing in the next several decades, and this will bring related environmental problems.

Because of the expected growth of electricity generation in developing countries, they are confronted with a variety of technological, economic and environmental problems. In industrialized countries the electric power sectors are concerned with environmental problems related mainly to electricity generation, but in many developing countries environmental issues are not considered to have high priority. The problems of the electricity sectors in the developing world differ among regions and countries [5].

3. SUSTAINABLE DEVELOPMENT

Sustainable development has three key elements: economic, environmental and social (Fig. 1). The economic approach to sustainability is based on the Hicks–Lindahl concept of the maximum flow of income that could be generated while at least maintaining the stock of assets (or capital) which yields these benefits [6, 7]. An underlying concept of optimality and economic efficiency is applied to the use of scarce resources. Problems of interpretation arise in identifying the kinds of capital to be maintained (manufactured, natural and human capital) and the possibilities for their substitution, as well as in valuing these assets, particularly ecological resources. The issues of uncertainty, irreversibility and catastrophic collapse pose additional difficulties [8].

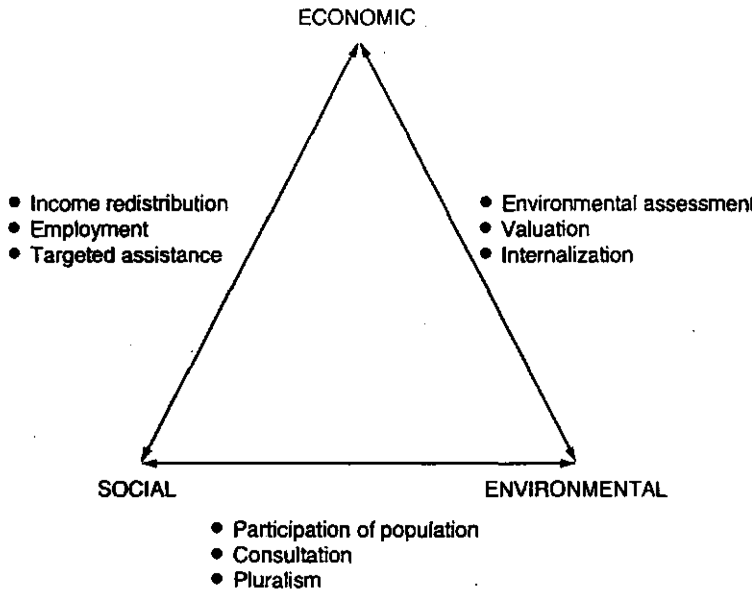

FIG. 1. Key elements of sustainable energy development.

The environmental view of sustainable development focuses on the stability of biological and physical systems. Of particular importance is the viability of subsystems that are critical to the global stability of the overall ecosystem [9]. Protection of biological diversity is a key aspect. Furthermore, 'natural' systems may be interpreted to include all aspects of the biosphere, including man-made environments such as cities. The emphasis is on preserving the resilience and the dynamic ability of such systems to adapt to change, rather than conservation of some 'ideal' static state.

The social concept of sustainability seeks to maintain the stability of social and cultural systems, including the reduction of destructive conflicts [10]. Intragenerational equity (especially elimination of poverty) and inter-generational equity (involving the rights of future generations) are important aspects of this approach. Preservation of cultural diversity across the globe should be pursued and better use made of the knowledge concerning sustainable practices that are embedded in less dominant cultures. Modern society would need to encourage pluralism and to increase the power and the participation of 'grass-root' politicians in order to provide a more effective decision making framework for socially sustainable development.

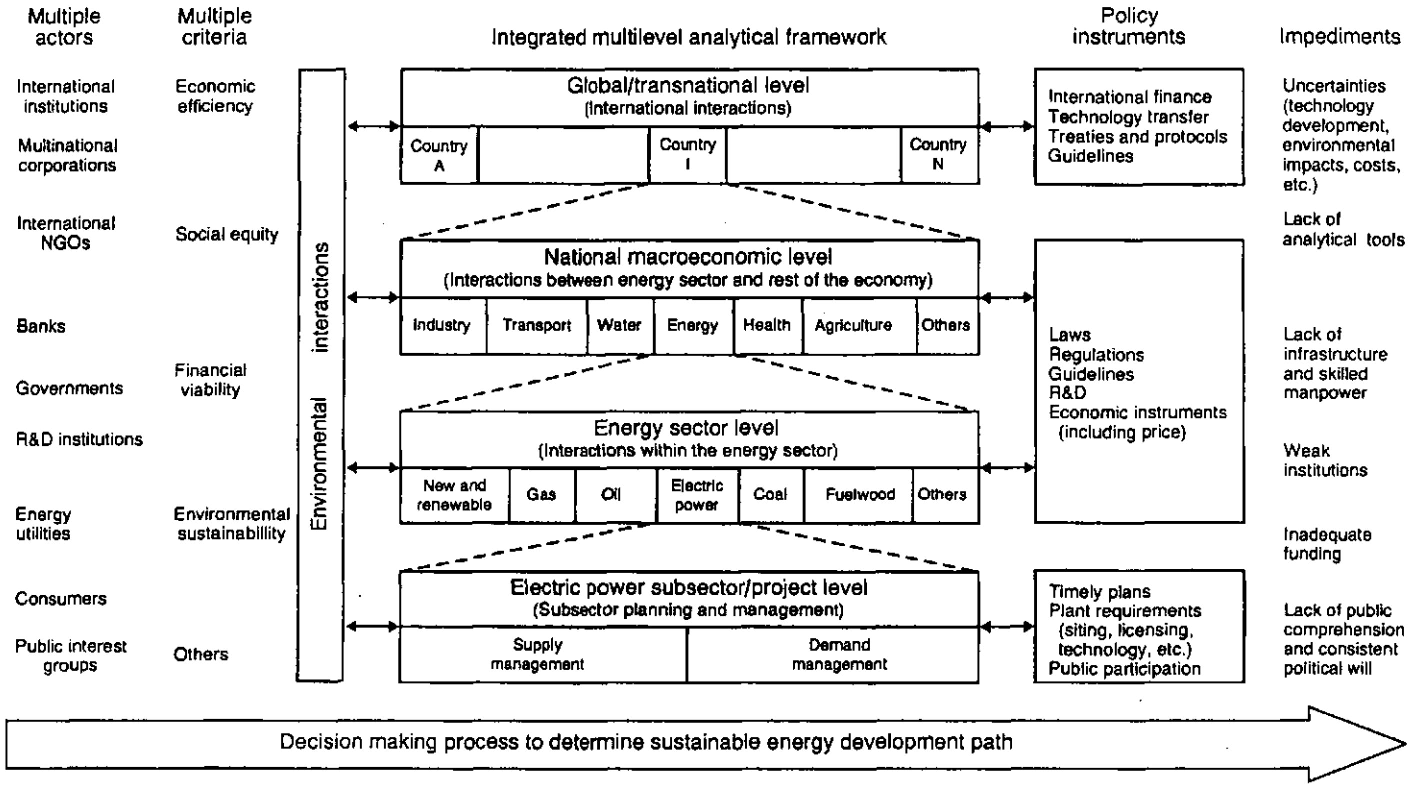

FIG. 2. Integrated framework for implementing sustainable energy development.
Source: Munasinghe.

4. SUSTAINABLE ENERGY DEVELOPMENT: ISSUES AND PROBLEMS

Given the rapidly increasing demand for energy, particularly electricity, in developing countries and the corresponding increase in investment requirements, the need for a comprehensive and integrated conceptual framework for analysis and decision making is evident. Sustainable energy options may be identified by using a framework that takes into account multiple actors, multiple criteria, multilevel decision making, and many impediments and constraints (Fig. 2). It is important to consider environmental and social implications of energy use, which can be broadly categorized into national, transnational and global issues.

4.1. National issues

While electricity has relatively few environmental and health consequences at the point of end-use, the same cannot be said for electricity generation. However, the extent and nature of impacts differ among energy sources.

In the case of *fossil fuels*, a significant public health risk results from the exposure to large amounts of gaseous and solid wastes discharged in the combustion process. These pollutants cause many health related problems. *Nuclear power* generates long lived, highly radioactive wastes and causes groundwater contamination. *Hydroelectric power generation* has primarily local environmental and social consequences, for example the damage caused by dam construction: destruction of habitats and loss of local and/or national biodiversity, the inundation of productive land and forests, siltation, and possibly the loss of cultural sites and mineral resources.

While *solar energy* techniques pose no significant occupational and health risks at the generation stage, some environmental impacts of solar thermal generation may arise from the loss of land use resulting from its large land requirements. *Geothermal steam* carries with it a number of atmospheric pollutants, including carbon dioxide, mercury and radon. With current technologies, the toxins are commonly reinjected into the reservoir. Problems with *biomass energy* use concern the effects of fuelwood plantations on the local environment; these concerns impose major constraints on the widespread adoption of dendrothermal power supply schemes. Although *wind power* generators do not produce air or water emissions, planners often face public opposition because larger turbines have a visual impact on the landscape, emit acoustic noise, generate electromagnetic interference and are a hazard to birds. There is some environmental concern about the effects of *ocean energy* technology on sea life and about atmospheric release of carbon dioxide from deep ocean waters.

4.2. Transnational issues

Acid deposition is perhaps the most serious of the transnational issues faced today. Acid deposition results from sulphur and nitrogen oxides that originate from fossil fuel combustion and fall to the ground as particulates and acid rain. Coal and oil fired power stations emit significant amounts of sulphur dioxide and nitrogen oxides to the atmosphere. Acid deposition caused by sulphur and nitrogen oxides results in damage to trees and crops, and sometimes leads to acidification of streams and lakes, resulting in destruction of aquatic ecosystems. It also leads to corrosion, erosion and discolouration of buildings, monuments and bridges. Indirect health effects are caused by the mobilization of heavy metals in acidified water and soil [11].

Other important transnational issues include environmental and health impacts of radiation from severe nuclear accidents (Chernobyl), oceanic and coastal pollution due to oil spills (Amico Cadez, Exxon Valdez and Braer), downstream siltation of river water in one country which is due to deforestation of water sheds and to soil erosion in a neighbouring country, and changes in hydrological flow and water conditions caused by dams.

4.3. Global issues

Increase in atmospheric concentrations of CO_2 and other radioactive trace gases (N_2O, CH_4; and chlorofluorocarbons or CFCs) is the likely cause of at least part of the recent increase in the mean global temperatures, i.e. 0.3–0.6°C in the past hundred years. Recent changes in rainfall patterns and the frequency of storms may also be attributable to this phenomenon. Over the past hundred years, the global sea level has increased by 10–20 cm [11].

The contribution of electricity generation to overall global warming (mainly in the form of CO_2 emissions) has been estimated at about 25%, compared with about 14% caused by deforestation; coal and oil contribute about 40% each of the anthropogenic CO_2 emissions, and gas contributes about 15%.

5. SUSTAINABLE ENERGY DEVELOPMENT: OPTIONS AND POLICIES

In considering sustainable energy options, policy makers must take into account all three aspects of sustainable development (economic, social and environmental). Options that lead to improvements in all three indices are referred to as 'win–win' options. Once 'win–win' options are realized, policy makers will be able to make trade-offs among other available options.

5.1. Identifying sustainable energy options: 'win–win' options versus trade-offs

Incorporation of environmental externalities into decision making is particularly important in the power sector, where environmental concerns (ranging from greenhouse gas emissions of fossil fuelled plants to the impacts of inundation from hydro plants) have posed increasing constraints on project implementation. It is also clear that in order for environmental concerns to play a role in power sector decision making, these issues must be addressed early — at the sectoral and regional planning stages rather than only at the stage of environmental assessment of a project.

Unfortunately, when dealing with power sector issues at an aggregate planning level, the application of many project level valuation techniques becomes extremely difficult, for two main reasons. The first reason is the nature of the impacts themselves; the health effects of pollutants from coal fired generating stations, the potential loss of biodiversity associated with large scale hydro reservoirs and the impacts of greenhouse gas emissions are all extremely difficult to value. Indeed, attempts to do so would very likely focus attention on the validity of the valuation techniques themselves rather than on the policy trade-offs that must be made. The second reason concerns the scale of analysis. Many techniques that are used are most appropriate at the micro-level: the contingent valuation approach is much more valid if people can be asked specific questions about the impacts of a particular project to which they can relate. However, this may be very difficult to apply in situations where one is dealing with a potentially large number of technology, site and mitigation options.

It is in these kinds of situation that the techniques of multicriteria analysis (MCA) may be applied. Such techniques first gained prominence as practical evaluation tools in the 1970s, when the intangible environmental externalities lying outside the conventional cost–benefit analysis (CBA) methodologies were increasingly recognized. MCA also met one objective of modern decision makers, who preferred to be presented with a range of feasible alternatives as opposed to one 'best' solution. MCA permits the appraisal of alternatives with differing objectives and varied costs and benefits, which are often assessed in different units of measurement.

MCA offers policy makers an alternative when the progress made to achieve multiple objectives cannot be measured in terms of a single criterion (i.e. monetary values). One example is the case of an efficient fuelwood stove — an end-use option for sustainable energy development. While the economic value of an efficient fuelwood stove is measurable, its contribution to social and environmental goals cannot be valued easily in terms of money. Figure 3 shows the effects and trade-offs of different options with regard to three indicators: economic efficiency (net monetary benefits), social equity (improved health) and environmental pollution (reduced deforestation).

The policy options can be assessed as follows: Triangle ABC in Fig. 3 indicates the existing fuelwood stove, with moderate economic efficiency, low social

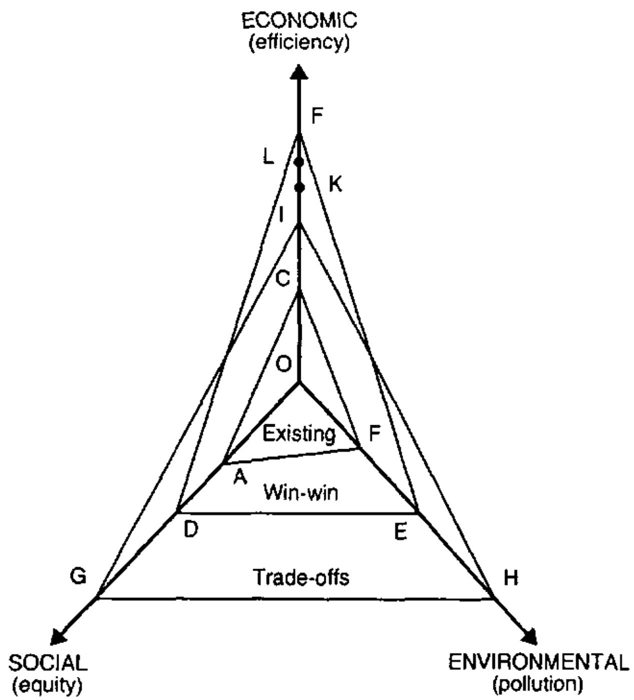

FIG. 3. Options for sustainable energy development.

equity and strong overall environmental impact. Triangle DEF indicates a future 'win–win' option in which all three indices improve, as could occur with an improved fuelwood stove that would provide energy and health benefits to the poor. The economic gains would include monetary savings from reduced fuelwood use and increased productivity of people due to reductions in acute respiratory infections, lung disease and cancer caused by pollutants in the smoke from biomass. Social gains would accrue from the fact that the poor people in rural areas would benefit most from this innovation; for example, because of the reduced time spent on collecting fuelwood, more time could be spent on other productive activities, and the health and labour burden on women and children would be reduced. The environmental benefits due to the lower demand for fuelwood will reduce deforestation and greenhouse gas emissions resulting from inefficient combustion [12].

After realizing gains from such 'win–win' options, the introduction of further options may require trade-offs to be made. Triangle GIH in Fig. 3 indicates that further environmental and social gains are only attainable at the expense of sharply increasing costs. For example, the shift from fuelwood to liquefied petroleum gas

(LPG) or kerosene as a fuel may increase the economic costs, while yielding further environmental and social benefits. In sharp contrast to the move from ABC to DEF, which is unambiguously desirable, a decision on a further shift from DEF to GIH may be difficult to make since policy makers would have to know the relative weights that society places on the three indices. Such preferences are often difficult to determine explicitly, but it is possible to narrow the range of options. Suppose a small economic cost (F–L in Fig. 3) yields the full social gain (D–G), while a large economic cost (L–I) is required to realize the environmental benefit (E–H). Here, the social gain may justify the economic sacrifice. Further, if purely budgetary constraints limit the costs to less than those for F–K, then there are only sufficient funds for the social benefits, and the environmental improvements will have to be deferred.

A recent World Bank study of power system planning in Sri Lanka demonstrated the versatility of the MCA approach. In this case, end-use energy efficiency measures provided 'win–win' options (i.e. they were superior to all other alternatives regarding air quality, loss of biodiversity and economic costs). Conversely, several prominent hydropower projects could be excluded because they performed poorly in terms of both loss of diversity and economic costs.

5.2. Options of sustainable energy development

In many countries, especially those in the developing world, inappropriate policies have encouraged wasteful and unproductive uses of some forms of energy. In such cases, better energy management could lead to improvements in economic efficiency (higher value of net output produced), energy efficiency (higher value of net output per unit of energy used), energy conservation (reduced absolute amount of energy used) and environmental protection (reduced energy related environmental costs).

However, it may not always be possible to satisfy all of the above goals simultaneously. For example, in some developing countries where the existing levels of per capita energy consumption are very low and certain types of energy use are uneconomically constrained, it may become necessary to promote energy consumption in order to raise the net output (thereby increasing economic efficiency). Apart from this particular case, there are many instances where it may be possible to increase energy efficiency while decreasing energy consumption.

The economic efficiency criterion, which helps maximize the value of net output from all available scarce resources (including energy), should include purely energy oriented objectives such as energy efficiency and energy conservation. Furthermore, the costs arising from energy related adverse environmental impacts may be included (to the extent possible) in the analytical framework of energy economics to determine how much energy use and net output society should be willing to forego in order to abate or mitigate environmental damage.

Energy use and energy generation in the developing world can be improved in two main ways to make them more sustainable. Firstly, energy efficiency can be increased by improvements on the supply and demand side. The energy use of developing countries is about 25% less efficient than that of OECD countries [13]. Thus, there is great scope for demand side management. Along with this, environmentally more benign technologies, such as clean coal technologies, cogeneration and gas turbine combined cycle technologies, can be introduced. Fuel switching and the use of renewable energy sources are two important technology changes that should be implemented in the developing world. In addition, options such as price reform and institutional and regulatory reform can be further implemented in order to achieve the required objectives of sustainable energy development (SED).

5.3. Matrix of SED options

Table II summarizes the impacts of the various options on the three elements of sustainable development. While for efficient supply side options (i.e. reductions in losses due to electricity transmission and distribution) there are clear economic gains in terms of savings in capital investments and environmental benefits from reductions of greenhouse gas emissions resulting from increased electricity supply, there are no obvious social benefits. Efficient end-use options, such as the provision of an efficient fuelwood stove, have benefits relating to all three elements. Although advanced technologies such as clean coal combustion technologies are essential for reducing air pollutants such as CO_2 and NO_x that cause respiratory diseases and reduce productivity, many developing countries cannot afford such high cost technologies. Likewise, renewable energy sources also provide environmental and social benefits by reducing a country's dependence on traditional fossil fuels. However, in terms of generating costs, renewable fuels are more expensive than fossil fuels.

TABLE II. MATRIX OF SED OPTIONS

Option	Impact		
	Economic	Environmental	Social
Supply efficiency	+	+	
End-use efficiency	+	+	+
Advanced technologies	−	+	+
Renewables	−	+	+
Pricing policy	+	+	+/−
Privatization/decentralization	+	+/−	+/−

6. SUSTAINABLE ENERGY DEVELOPMENT: A CASE STUDY OF SRI LANKA

An MCA based approach was used by Meier and Munasinghe [14] in a study of Sri Lanka. The objective of this study was to demonstrate how environmental externalities can be incorporated into power system planning in a systematic and efficient manner. At present, Sri Lanka depends largely on hydropower for electricity generation, but for the next decade there seems little choice other than to begin building large coal or oil fired stations, or to build hydro plants, whose economic returns and environmental impacts are increasingly unfavourable. In addition, there are a wide range of other options (such as wind power, increasing use of demand side management, and improvements in system efficiency) that make decision making quite difficult, even in the absence of environmental concerns. The study is unique in its focus on these kinds of planning issues, as opposed to the more usual policy of assessing environmental concerns only at the project level, after the strategic sectoral development decisions have already been made.

6.1. Environmental issues

Sri Lanka is one of the more densely populated countries of the world, and land availability is an important issue. In general, hydro plants are in the wet zone areas where there is little vacant land nearby for relocation of inhabitants, while land that is available at greater distances is often regarded by potential evacuees as undesirable because of inadequate water supply. A rough but effective way of comparing the likely extent of the potential land related environmental impacts of projects is to use as a parameter the area inundated per kilowatt-hour of capacity. This varies between zero and as much as 150 ha/kW·h. The correlation between the installed capacity and the amount of land to be inundated is poor; large projects do not necessarily mean greater environmental impacts and vice versa.

The progressive loss of Sri Lanka's natural forests over the past 50 years is well documented and is one of the country's most important environmental concerns. Power sector projects will be scrutinized very carefully for their potential impact on natural forest areas, even if it is true that the power sector per se has been a relatively minor contributor to the loss of forest lands.

Relatively little is known about the air quality in Sri Lanka. In most parts of the country the air quality is fairly good, because of the limited extent of industrialization (except in Colombo) and because of the natural ventilation provided by strong monsoon winds. It is fairly certain that at present the power sector contributes only marginally to air pollution in Sri Lanka. However, this is expected to change significantly once the anticipated coal burning power plants are added to the system in the late 1990s.

Acid rain is likely to become an increasingly important environmental issue in the Asian–Pacific region, given the fact that in many countries, in particular India and China, a rapid development of fossil energy systems is planned. Acid rain is largely a long range phenomenon, and it is fairly obvious that the extent to which acid rain is being or will be experienced in Sri Lanka is as much a function of emission trends of acid rain precursors in India as it is a function of such trends in Sri Lanka itself.

Global warming and transnational acid rain are conceptually different from local environmental impacts, since in the former case the impacts will occur predominantly in other countries. If the main economic objective were to maximize welfare in Sri Lanka, decision makers in Sri Lanka would be unwilling to incur additional costs if the benefits of such actions accrue mainly to other nations. In this case study, it is assumed that Sri Lanka will be reimbursed by the international community for the incremental costs of efforts to mitigate global warming, or that the Government will sign an international agreement, committing itself to undertake certain measures to reduce CO_2 emissions.

Because Sri Lanka is a small island (65 000 km^2), which was isolated for relatively long periods, there are a large number of endemic species. Among Asian countries, Sri Lanka has the highest level of biological diversity. The Committee on Research Priorities in Tropical Biology of the United States National Science Foundation identifies Sri Lanka as demanding special attention. Biological diversity is threatened in Sri Lanka primarily because of the progressive reduction of its natural forests and other natural habitats, especially through selective exploitation of tree species, particularly for timber. Therefore, the power sector is likely to come under intense scrutiny from this perspective.

As the electricity generation mix shifts from one that is based predominantly on hydropower to one in which large base load fossil fuelled plants play an increasing role, sites will need to be found on the coast to accommodate such thermal plants. The economic importance of preventing environmental degradation in the coastal zones is well established. Foreign tourism, an important source of foreign exchange, is largely focused on the country's sandy beaches and coastal estuaries and lagoons. The marine fishery industry provides employment to some 100 000 persons and is the largest source of animal protein for Sri Lanka. The main environmental issue concerns the discharge of heated effluents into waters of the coastal zone, where there exist numerous ecosystems that are extremely sensitive to temperature increases, including coral reefs, sea grass beds, benthic communities, mangrove stands, rocky and other shores, zooplankton and phytoplankton communities which are free floating, and nursery grounds for fish and prawns.

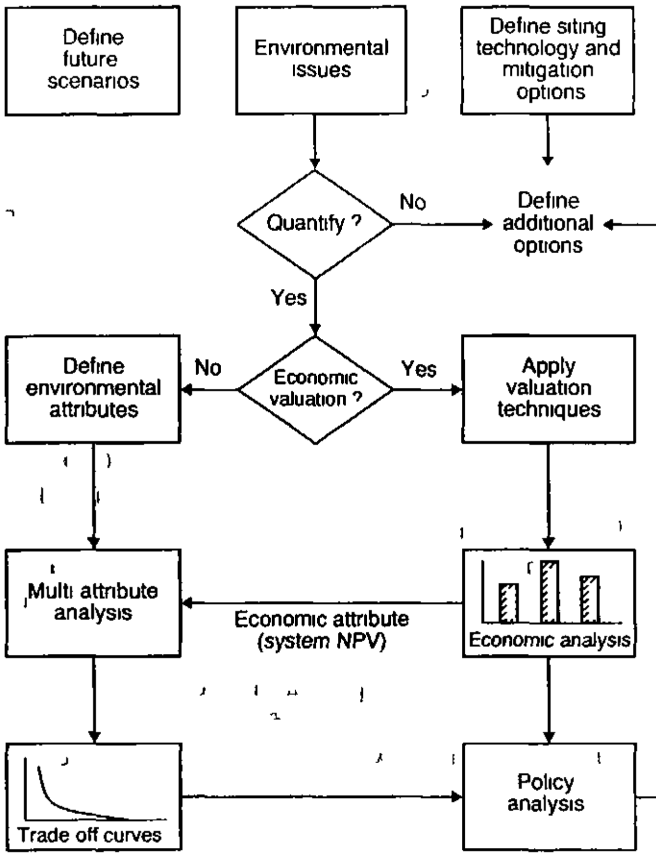

FIG 4 General methodology for environmental analysis of power systems Source Meier and Munasinghe [7]

6 2 Methodology

Multicriteria analysis has been developed expressly for situations where decisions must take into consideration more than one objective that cannot be reduced to a single dimension The central focus of MCA is on quantification display and resolution of trade offs that must be made when there are conflicting objectives In the case of application to the power sector there may well be strategies that have beneficial impacts on both environmental and economic objectives — most energy efficient investments that are economically justifiable also bring about a reduction in emissions and hence improve the quality of the environment as well as economic efficiency For most options however it is necessary to make trade offs wind plants, for example, may provide substantial environmental benefits, but they are more expensive than other options.

The overall methodology is illustrated in Fig. 4 and involves the following steps:

(1) Definition of the options to be examined.
(2) Selection and definition of the attributes chosen to reflect the planning objectives.
(3) Explicit economic valuation of those impacts for which valuation techniques can be applied with confidence. The resultant values are then added to the system costs to define the overall cost attribute.
(4) Quantification of those attributes for which explicit economic valuation is inappropriate but for which suitable quantitative impact scales can be defined.
(5) Translation of attribute value levels into value functions (known as 'scaling').
(6) Display of the trade-off space to facilitate the understanding of the trade-offs to be made in decision making.
(7) Definition of a candidate list of options for further study; this also involves the important step of eliminating from further consideration options that are clearly inferior.

In some applications it may be appropriate to add two further steps: definition of weights for each attribute and application of an amalgamation rule to provide a single overall ranking of options. However, the Sri Lanka case study did not follow this approach.

6.3. Application of MCA to the power sector in Sri Lanka

6.3.1. Definition of the policy options

A variety of options were selected for study, including a whole range of siting, pollution control mitigation and technology options. Indeed, it is very important to make as few a priori judgements as possible about the 'feasibility' or 'practicality' of options because, for the analysis to be useful, meaningful trade-offs must be examined. For example, in the case of the Trincomalee coal fired power plant (on the north-east coast), the environmental impact assessment prepared in the mid 1980s considered only a very narrow range of options: all alternatives studied involved sites on Trincomalee Bay, with once-through cooling and discharge of effluents to a shallow bay inlet. Other sites on the south coast had been eliminated earlier because of high cost (these sites could not accommodate large coal transport vessels, resulting in higher transport costs). Yet the additional costs of an evaporative cooling system or of an outfall system that would discharge heated effluents to the deeper parts of Trincomalee Bay proved to be less than the incremental costs for coal transport to a site on the south coast.

The main set of policy options examined, beyond variations in the mix of hydro and thermal plants, included: (1) demand side management (using the illustrative example of compact fluorescent light bulbs); (2) renewable energy options (using the illustrative technology of wind generation); (3) improvements in system efficiency (with more ambitious targets for transmission and distribution losses than the base case assumption of 12% by 1997); (4) clean coal technology (using pressurized fluidized bed combustion (PFBC) in a combined cycle mode as the illustrative technology); and (5) pollution control technology options (illustrated by a variety of fuel switching and pollution control options, such as using imported low sulphur oil for diesel plants and fitting coal burning power plants with flue-gas desulphurization (FGD) systems).

6.3.2. Selection of attributes

Great care needs to be exercised in the selection of criteria or attributes, i.e. they should reflect issues of national (as opposed to local project level) significance and ought to be limited in number. Little can be gained from a proliferation of attributes. Increasing the number of attributes is not a substitute for assigning proper weights to environmental attributes in the decision making process. On the contrary, the more attributes are considered, the more complex the analysis and the higher the probability that the results will be difficult to interpret and that decision makers will not find the exercise useful. It often occurs that, in a desire to be comprehensive, all possible impacts are included, making it more difficult to demonstrate trade-offs and possibly introducing biases through a reluctance to assign low weighting to attributes.

The following environmental criteria or attributes were used in the study. To capture the potential impact on global warming, CO_2 emissions were defined as the appropriate proxy. The relationships between global CO_2 concentrations and the actual physical impacts, such as a rise of the sea level or changes in monsoon rainfall patterns, are still poorly understood and in any event unlikely to be captured by simple linear correlations. However, since Sri Lanka's contribution to worldwide emissions will remain extremely small, the assumption of a linearity of the impacts (relative to global CO_2 emissions) is not unreasonable.

To capture health impacts, use was made of the population weighted increment in fine particulates and in nitrogen oxides attributable to each source. To this end, a simple Gaussian plume model was applied to all of the major sites; incremental ambient concentrations for 1 km^2 cells were calculated to within a 20 km radius and then multiplied by the number of people in each cell.

To capture other potential air pollution impacts, such as acid rain, emissions of sulphur dioxide and nitrogen oxides were used. As an illustrative social impact, the study used the creation of labour opportunities. Creation of employment is an important objective of national policy, and in Sri Lanka there was frequent discussion of the need for employment creation in the south where the unemployment rates of young people are especially high It should be noted that what is captured in this attribute is the separate and purely political objective of employment creation which is to be distinguished from the strictly economic benefits that would be captured by the use of shadow wage rates appropriate to reflect high unemployment in the construction cost estimates All of these impacts were appropriately discounted and expressed as a present value Finally to capture the potential impacts on bio diversity a probabilistic index was derived (as discussed below)

6 3 3 Quantification of attributes

The problems of quantification are well illustrated in the case of the bio diversity attribute It is unlikely that at the planning level detailed site specific information on the potential power plant sites is available Consequently the only quantification that appears possible is to derive a probabilistic index providing infor mation about the likelihood that the detailed environmental impact statement will reveal the presence of an endemic species will significantly impact ecosystems of high biological diversity or will affect a habitat that is already in a marginal condition

There are a number of practical problems in deriving an appropriate index First the value of the area lost is a function of the remaining part of the habitat For example the loss of the last hectare of an ecosystem would be unacceptable whereas the loss of one hectare if 1000 hectares remain would be much less serious Second ecosystems may require a minimum area for long term survival which implies that the value function would need to tend to infinity as it approaches that minimum value Perhaps even more importantly the argument is sometimes made that the value to be ascribed to the loss of habitat associated with some regulatory or govern mental decision depends on whether the habitat remains secure

Some impacts however resist direct quantification even in terms of the sort of probabilistic scale derived for biodiversity For example the quantification of potential damages to aquatic ecosystems from thermal discharges is extremely problematic largely because of the difficulties in extrapolating from one ecosystem to the other The general effects of thermal discharges into coastal waters are of course well known Discharges into the well mixed surface layer would usually tend to repel fish On the other hand if the discharge is below the thermocline thermal discharges would have a generally beneficial effect as the upwelling effect caused by plume buoyancy brings nutrients to the layers near the surface However it is impossible to give specific numerical estimates for the values of this general func tion What can be done in a generic calculation that can be used to compare different sites is to use initially a definition of what is considered to constitute an acceptable environmental risk for example a temperature increase of no more than 1 °C at the surface The surface area over which this criterion is exceeded is then calculated as a function of the cooling system design proposed

6 4 Some illustrative results

When the options and attribute definitions were available the multidimensional trade off space was generated in the case study Using the ENVIROPLAN model the values for each of the environmental attributes and the cost attribute (for which an average incremental cost over a 20 year planning horizon was used) were calcu lated for every option with the results displayed as a series of two dimensional trade off curves In a final step the list of candidate plans for further study was derived by examining the dominant relationships among all criteria simultaneously

Figure 5 illustrates a typical trade off curve in this case for health impacts The best solutions are those that lie closest to the origin and the so called trade off curve defined by the set of non inferior solutions represents the set of options that are superior regardless of the weights assigned to the different objectives For

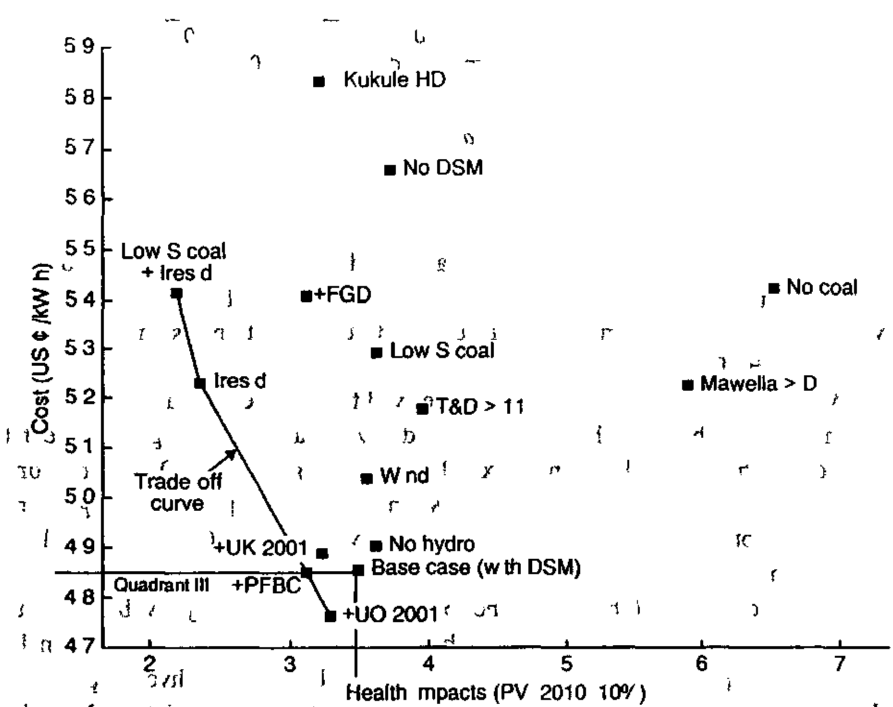

FIG 5 Cost versus health mpacts Source Me er and Munas nghe [7]
HD = h gh dam DSM = demand s de management PFBC = pressurized flu d zed bed convers on FGD = flue gas desulphurizat on

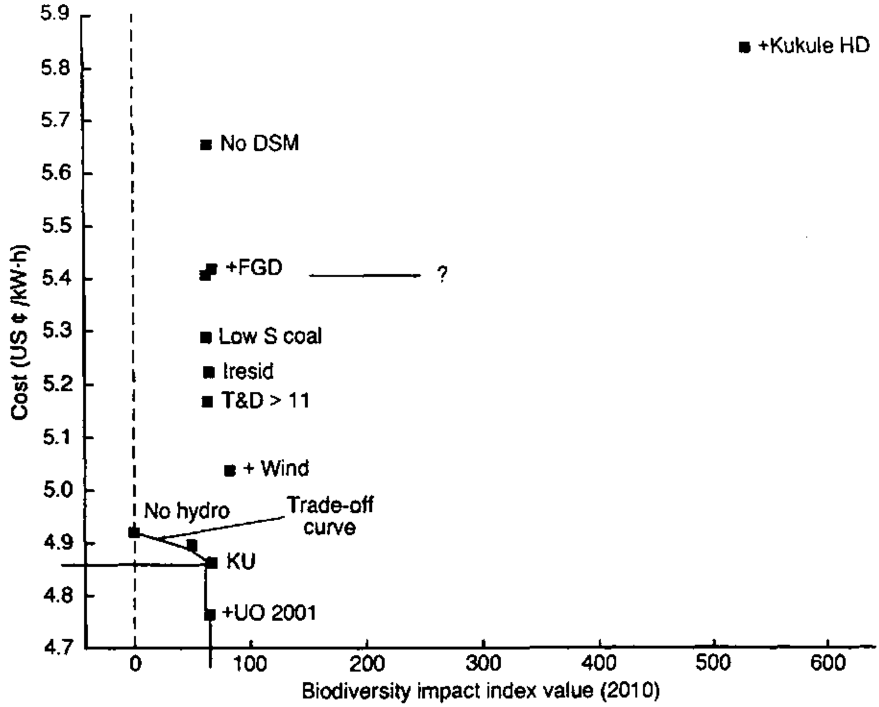

FIG. 6. Cost versus biodiversity impacts. Source: Meier and Munasinghe [7].

example, on this curve, the option defined as 'iresid', which calls for the use of low sulphur imported fuel oil at diesel plants, is better as regards both the cost and the environmental objective than the use of flue-gas desulphurization systems (identified as the point 'FGD').

A quite different trade-off curve was derived for biodiversity, and Fig. 6 illustrates the trade-off between the biodiversity index value and the average incremental cost. Most of the options have an index value in the range of 50–100: the no-hydro option has an essentially zero value because the thermal projects replacing hydro plants in this option tend to lie at sites of poor biodiversity value (either close to load centres or on the coast). For example, wind plants would require a rather large land area, but the vegetation of the area on the south coast has a relatively low biodiversity value and therefore the overall increase in biodiversity impact of this option is small. Thus, the best options (or the non-inferior curve) includes the no-hydro option, as well as run-of-river hydro options that require essentially zero inundation. Note the extreme outlier at the top right hand corner, which is the Kukule hydro dam: it has a biodiversity loss index (B = 530) that is an order of magnitude larger than that for other options (B = 50–70).

The case study has drawn several useful conclusions. The first four listed below are of a methodological nature and deal with the extent to which multi-attribute methods are potentially effective in assisting decision makers. The remaining conclusions deal with the substantive policy recommendations whose focus is to ensure that environmental considerations are appropriately incorporated in the planning process.

First, the case study indicated that those impacts for which valuation techniques are relatively straightforward and well established, such as valuing the opportunity costs of lost production from inundated land or estimating the benefits of establishing fisheries in a reservoir, tend to be quite small compared with the overall system costs, and their inclusion in the cost-benefit analysis does not greatly change results.

Second, even if explicit valuation may be difficult, such as in the case of mortality and morbidity effects of air pollution, implicit valuation based on an analysis of the trade-off curve can provide important guidance to decision makers. For example, it was determined that the value of human life justifying FGD at potential sites for coal fired power plants was of the order of US $1.5 million. This is at least one order (if not two orders) of magnitude greater than what would be needed to justify the installation of modern diagnostic equipment at regional hospitals.

Third, the case study indicated that certain options were in fact clearly inferior, or clearly superior, to all other options if all impacts are examined simultaneously. For example, the high dam version of the Kukule hydro project can be safely excluded from all further consideration because of the poor performance on all attribute scales (including the economic one). On the other hand, implementation of certain demand side management measures dominates all other options, i.e. such measures yield positive gains in terms of economic and environmental criteria.

Fourth, the case study indicated that it is possible to derive attribute scales that can be useful proxies for impacts that may be difficult to value. For example, use of the population weighted incremental ambient air pollution scale as a proxy for health impacts permitted a number of important conclusions that are independent of the specific economic value assigned to health effects. Thus, the study clearly demonstrated that with regard to the health effects of pollutants associated with fossil fuel combustion (particularly fine particulates and nitrogen oxides), the most effective strategy for reducing the overall population dose is to install devices for better control of pollution at oil burning power plants located in or near urban areas, rather than installing FGD systems at the more remote sites suitable for coal burning power plants.

Finally, with respect to the practical implications for planning, the study provided a series of specific recommendations on priority options, including: (1) the need to systematically examine demand side management options, especially the use of fluorescent light bulbs; (2) the need to examine whether the present transmission and distribution loss reduction target of 12% ought to be further reduced; (3) the need to examıne the poss b l t es of the PFBC technology for coal f red power plants (4) replacement of some coal fired power plants (on the south coast) by d esel units and (5) the need to re exam ne cool ng system opt ons for coal f red plants

7. CONCLUSIONS

Increasing levels of energy related environmental degradation in both industrialized and developed countries have led to recognition of the need for improved energy options for sustainable development. It is the primary objective of such options to maximize the net economic benefits of energy development while maintaining the stock of economic, ecological and socio-cultural assets for future generations and providing a safety net to meet basic needs and to protect the poor. Sustainable energy options may be identified using a comprehensive and integrated framework for analysis and decision making that takes into account multiple actors, multiple criteria, multilevel decision making, and a number of impediments and constraints. In the past, the principal planning objective of energy development was to meet the anticipated needs at the lowest economic cost. At present, environmental and social concerns must also be incorporated early at the regional and sectoral planning stages in order to ensure sustainable energy development. However, difficulties in valuing certain environmental and social impacts of energy development and the existing large number of options may require the use of MCA techniques rather than conventional CBA methods, to provide a range of feasible alternatives as opposed to one best solution. Using MCA, 'win–win' energy options that satisfy all three elements of sustainable development (economic, environmental and social) can be identified and then trade-offs from other available sustainable energy options can be made. A case study of the power sector in Sri Lanka demonstrates how MCA techniques can improve decision making.

Increased co-operation between industrialized and developing countries is required when dealing with energy related environmental and social issues. Developing countries have limited capabilities to address global environmental concerns. Without enhanced flows of incremental technical and financial resources from industrialized countries, it will not be possible to enhance the prospects for more sustainable energy development, worldwide.

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FRAMEWORK FOR AND CURRENT ISSUES IN COMPREHENSIVE COMPARATIVE ASSESSMENT OF ELECTRICITY GENERATING SYSTEMS

S. HIRSCHBERG
Paul Scherrer Institute,
Würenlingen and Villigen,
Villigen, Switzerland

Abstract

FRAMEWORK FOR AND CURRENT ISSUES IN COMPREHENSIVE COMPARATIVE ASSESSMENT OF ELECTRICITY GENERATING SYSTEMS.

The paper addresses a selection of methods used within the comprehensive assessment of energy systems. The focus is on electricity production, although the presented framework has a broader scope of applicability. The areas covered include environmental inventories and impacts, risks, economic aspects and support for decisions. The merits and limitations of the methods used are discussed and illustrated by a number of examples of results. Progress achieved with respect to the treatment of a number of difficult issues, such as database completeness, analysis boundaries, representation of technological advancements and treatment of severe accidents, is reported. It is beyond the scope of the paper to cover the wide spectrum of alternative approaches that could be employed within the comparative assessment. Instead, the main emphasis is on the methods used within the current Swiss research programme evaluating the options for the long term, strategic national energy planning. Life cycle analysis (LCA) is used to analyse environmental inventories and, in its extension, also the associated impacts. Transparent, detailed and consistent inventories have been developed for electricity generating and heating systems. The results, which include gaseous and liquid emissions as well as non-energetic resources such as land depreciation, cover average, currently operating systems in the network of UCPTE (Union pour la coordination de la production et du transport de l'électricité) and in Switzerland. This analysis has been extended to include advanced electricity supply systems considered to be of potential interest for the future electricity supply in Switzerland. In view of the limitations of LCA with regard to impact assessment, in a parallel effort a flexible framework and tool are being developed for the establishment of correlations between the emission rates of air pollutants originating from the Swiss energy system and the resulting concentrations and impacts; transport, chemical conversion and deposition are considered in detail in this context. There are major gaps with respect to the assessment of the severe accident potential within the different energy systems. When analysing the objective risk due to severe accidents, two approaches are employed, i.e. direct use of past experience and applications of probabilistic safety assessment. Within energy economics, the Swiss version of MARKAL (large scale 'bottom-up' energy–economy model) is extensively applied to future scenarios under environmental constraints. A complementary approach — sector specific studies focusing on impacts of energy conservation — allows the influence of market structures and of the strategic behaviour of relevant actors to be examined. Finally, several options for decision support are briefly discussed.

1. INTRODUCTION

1.1. Experiences from previous studies

A number of methodological issues in comparative assessment of the impacts of environmental and health effects of electricity systems were identified in the Key Issues Paper No. 3 presented at the Senior Expert Symposium on Electricity and the Environment [1]. Using this as a starting point, broadening the scope to include energy economics and emphasizing some points of improvements reflected in the present paper, the following conclusions were drawn [2]:

(1) There exists no standard for a consistent definition of boundary conditions for comparative analyses.

(2) Dose response relationships for the health effects of emitted major pollutants (such as SO_x, NO_x, non-methane volatile organic compounds (NMVOC), particulates, organic matter and heavy metals) are subject to very large uncertainties. In current assessments for fossil fuels, mostly only the impacts of SO_2 have been taken into account. Data on delayed and chronic effects are incomplete and not well established. Examples of factors that contribute significantly to the complexity in the evaluation of the health risk impact are the weighing of time delays of biological damage, the possibility of threshold versus linearity in dose effect relationships, the age and gender dependence on the impact of exposure, and possible synergy effects accelerating and aggravating the biological damage.

(3) Methods and data for the assessment of the environmental impacts of different energy sources are not well developed. While emission rates can be reasonably well established, it appears that the development of models and the collection of the necessary data for the dispersion of pollutants, and their complex interactions with the natural environment and associated ecosystems under a multitude of different conditions are extremely difficult tasks. Not all effects that are important in this context can be quantified. Large uncertainties are associated with the assessment of recoverability versus irreversibility of damage. Consequently, the present approaches are mostly qualitative and not very suitable for comparative studies. The recently developed critical load and critical level concept is an exception, since it is a quantitative approach that could be used to obtain comparative risk estimates. There is a need to define relevant indicators for environmental effects and to apply them in a consistent manner.

(4) Severe accidents have not been covered in a satisfactory manner. The very incomplete evidence based on the actual experience of accidents provides only a partial picture of the risks associated with the different energy systems. First, the conditions (for example with respect to technology, physical environment, safety principles and culture) characteristic for a specific event may be such that its applicability to other conditions will be questionable, possibly precluded. The quality,

relevance and uncertainties associated with such an assessment may vary. Second, for some energy sources the accident related data are so scarce that, in the best case, only predictive estimates are available. Third, the main sources contributing to the risks are not always obvious, i.e. for some energy sources the operation of plants producing energy may not constitute the dominant risk factor; instead, the dominant contributions may originate from other parts of the fuel cycle (upstream and downstream processes) and/or from other stages of the plant life cycle.

(5) The time-scale for which the assessments are being made influences the choice of technology to be considered. The basic problem is that the technologies of the various energy systems are of different maturity. Thus, there is the unavoidable question of how to account for prospective advancements of technology.

(6) Limitations of databases constitute an intrinsic problem of comparative studies, which is the underlying main reason for the problem issues described above.

(7) With respect to energy economics, two different approaches can be distinguished, namely large scale models and sector specific studies. Large scale models are characterized by complex and comprehensive representation of interdependencies, thus allowing determination of the cost optimal configuration of energy systems. These models require, however, rather extensive resources and have limited transparency and flexibility. Sector specific studies, on the other hand, concentrate on single sectors/markets in which energy plays a role. They receive usually a positive public/political response, but may lead to rather heterogenous results and some important interrelations may be overlooked. Both approaches are associated with major uncertainties.

(8) Integration of the results originating from different parts of comparative studies has hardly been attempted. There is certainly a limit to the level of such integration beyond which the exercise may become meaningless. The questions as to where to put such a limit and what are the most suitable forms of integration are still open.

1.2. Framework example — the Swiss case

This paper provides examples of the progress made in the comparative assessment since the Helsinki Symposium, using primarily, but not exclusively, the ongoing Swiss project on comprehensive assessment of energy systems (Ganzheitliche Betrachtung von Energiesystemen — GaBE) [2] as the basis. The objective of this project is to develop, implement and use a comprehensive methodology for the consistent and detailed assessment of energy sources of interest under Swiss conditions and thereby to provide scientific support to the decision making process concerning the future configuration of the Swiss energy system [2]. The types of energy sources covered include fossil fuels, nuclear and renewables.

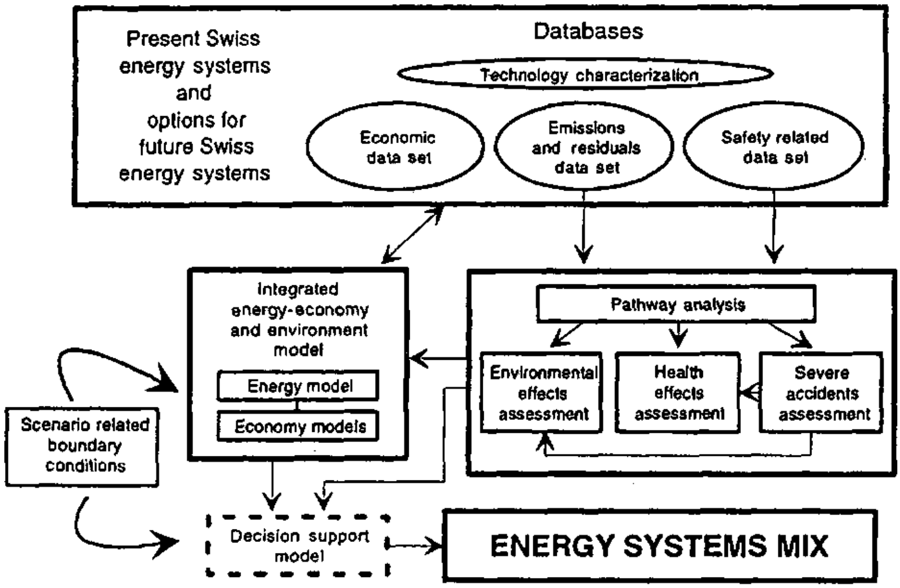


FIG. 1. Conceptual framework (GaBE) for assessment of energy systems [1].

Naturally, different frameworks could be defined for comparative analysis, depending on the objectives to be achieved. Since it is beyond the scope of this paper to provide an exhaustive review of possible frameworks, we refer to the extensive literature, including the recently published European Commission (EC)/US studies on external costs [3, 4]. In the Swiss case the focus is on the support of long term, national, strategic energy planning rather than on very specific short term utility planning. Therefore, the overall approach chosen is not necessarily directly transferable to other applications, although its different elements could be adjusted, depending on the needs and disposable resources. While the focus here will be on the electricity sector, in some cases the whole energy sector is addressed because of many important interactions and interdependencies.

Figure 1 shows the conceptual framework for the assessment of energy systems as used in the Swiss case. The basic approach encompasses the application of life cycle analysis (LCA) for each stage of the various fuel cycles to generate detailed material/energy flows and to establish an as complete as possible set of direct and indirect ('grey') emissions as well as of other residuals. Modelling of environmental impacts makes use of LCA and, in a parallel activity, also aims at an explicit establishment of correlations between the emission rates of air pollutants and the resulting concentrations and impacts for Switzerland. This forms a direct link to the assessment of health effects associated with the normal operation of energy systems.

Severe accidents are being analysed using the actual experience as well as the approach of probabilistic safety assessment (PSA). In view of the past experiences from energy-economy studies, use of a large scale model is combined with sector specific studies. Development and application of a decision support framework for an integrated analysis of the different disciplines are under consideration.

In the following sections, current issues within selected topical areas are discussed, together with examples of results. Because of the limited space available, energy economics will be treated to a very limited extent. Referring to the methodological issues summarized in Section 1.1, the progress made in the treatment of analysis boundaries, impact simulation, severe accidents and consideration of technological advancements will be illustrated.

2. LIFE CYCLE ANALYSIS FOR ENVIRONMENTAL IMPACT ASSESSMENT

Three steps are employed in the full LCA assessment: inventory, characterization/normalization and valuation [5].

2.1. Basic methodology for establishment of LCA inventories

Detailed descriptions of the basic LCA methodology used in the Swiss approach for the inventory step can be found in Ref. [6]. Some fundamental features are:

— Complete fuel cycles (fuel extraction and conversion, energy production, waste management) are covered.

— All systems are described on a 'cradle to grave' basis, with each step in the cycle being decomposed into construction, operation and dismantling processes.

— Not only direct (concentrated) emissions from the plants are covered but also indirect (grey or diffuse) ones, in order to provide an as complete as possible representation of the total environmental fluxes.

— A set of rules was established for the definition of system boundaries to achieve a high level of consistency and detail for all energy systems. Energy and material balances were established by linking about 500 process modules. The interactions between the systems were fully considered. For example, for mining and refining of coal there is also an input of the applicable electricity mix, which in turn may have a coal component.

— A very broad spectrum of resources (more than 200) and of air and water pollutants was covered. This also includes non-energetic resources; land depreciation and radioactive isotope emissions were treated with a high degree of detail.

- Material inputs and transportation needs were considered in connection with all steps of a fuel cycle; construction efforts and materials for road and rail infrastructure were also included in the analysis.
- A consistent set of data for material production, transportation, construction and disposal services was developed, to be used by all energy systems. Particular attention was given to materials used in large quantities in energy systems (concrete, steel, aluminium) as well as materials used in small quantities but having associated, potentially highly toxic, emissions during production, operation or disposal. Standard modules for transportation include road (trucks of different sizes, cars), rail, river (barges) and sea (ships and tankers). Standard disposal systems were defined, covering landfills, contained repositories, and industrial and communal incinerators.
- For electricity inputs, results from the average UCPTE (Union pour la coordination de la production et du transport de l'électricité) generation were used in all analyses of the currently operating systems. Services and materials that have been accounted for represent the average European (UCPTE) situation.
- Allocation criteria were developed for multi-output processes.

This methodology was first applied to the currently operating systems [6]. Consequently, the input was normally based on the operating experience. The results obtained for the current systems have only limited relevance as the input for decisions concerning preferred future configurations. Furthermore, the standard approach is static and its applications to future scenarios require extensions, extrapolations and additional assumptions. For these reasons, the existing data and the methodological basis were extended in order to reflect technological advancements and new options, as well as expected structural changes [7]. The extensions were based on literature, on direct information from the industry and from consultants, and on expert judgement. Availability of relatively detailed process information and knowledge of the relative importance of the various sources of emissions made it possible to focus the analysis and to economize the use of resources. The parts of fuel cycles identified as the most significant contributors to emissions and/or as being subject to major technological changes are:

Gas systems:	gas transport and power plant;
Coal systems:	mining, coal transport and power plant;
Nuclear systems:	mining/milling, enrichment, power plant, reprocessing;
Hydro systems:	power plant;
Photovoltaic (PV) systems:	manufacturing of solar cells.

The parameters of primary interest in the evaluation of advanced systems are: emissions, efficiencies, material intensities (for construction and operation) and transportation requirements. When selecting performance parameters, and having ranges of values as the starting point, the best values were normally chosen as the most representative for the time horizon under consideration (scenarios for the years 2020/2030). When in doubt, conservative rather than speculative values were applied.

2.2. Examples of results for and insights into LCA based inventories and their implications

Using the generated data as the basis, inventory comparisons were carried out for nine current energy chains for electricity generation [8]. This work covers analyses of, for example, greenhouse gases, SO_x, NO_x and NMVOC emissions, land use, radiation and wastes; the importance of considering full energy chains has been highlighted. Later, a detailed comparison of greenhouse gas (GHG) inventories was carried out using the same database [9].

Table I summarizes the results obtained for GHG emissions from systems operating in Switzerland and in UCPTE countries [9]. These results are based on full energy chain (FENCH) analysis and cover the direct and indirect contributions. The Swiss electricity supply is almost exclusively based on hydro and nuclear plants (together, 97.9% of the total), while the UCPTE mix has a large fossil component (47.9%). This explains the large differences between the results obtained for the Swiss and UCPTE mixes.

Figure 2 shows the corresponding results obtained for a variety of PV systems [9]. The values are between 81 and 257 g CO_2/kW·h for roof panels, 164 g CO_2/kW·h for the Swiss PHALK 500 plant (a 0.5 MW demonstration plant in Jura, operating since 1992), and 228 g CO_2/kW·h for a 100 kW plant located near a Swiss highway. The contribution of electricity to the total GHG emissions (the UCPTE mix is used for the production of the cells) is 80–90%; the remaining emissions are associated with material requirements.

For the advanced systems the most important changes (in terms of the impact on the results of the present analysis) in relation to the existing analysis of currently operating systems are:

- Gas systems: reduction of gas leakage, improvements of power plant burner performance characteristics and power plant efficiency;
- Coal systems: partial CH_4 recovery in underground mining, improvements of power plant abatement technology and power plant efficiency;
- Nuclear systems: reductions of long term radon emissions from mining/milling tailings, reductions of electricity consumption and of CFC emissions from enrichment by replacement of diffusion by centrifuge or laser technologies, improvements of power

TABLE I. GHG EMISSIONS ASSOCIATED WITH PRESENT SWISS AND UCPTE FENCHs FOR ELECTRICITY GENERATION AND CORRESPONDING ELECTRICITY MIXES [9]

Warming potentials according to IPCC 1992

GHG	Countries	Emissions from FENCH (t/GW·h from the relevant chain)						Mix (t/GW·h from mix)
		Lignite	Hard coal	Oil	Gas	Nuclear	Hydro[a]	
CO_2	Switzerland	NA	NA	8.59×10^2	NA	6.89×10^0	3.62×10^0	1.54×10^1
	UCPTE	1.33×10^3	9.73×10^2	8.71×10^2	7.51×10^2	8.14×10^0	3.99×10^0	4.82×10^2
CH_4	Switzerland	NA	NA	1.02×10^0	NA	1.73×10^{-2}	7.97×10^{-3}	2.43×10^{-2}
	UCPTE	2.69×10^{-1}	4.21×10^0	1.11×10^0	1.79×10^0	2.03×10^{-2}	8.82×10^{-3}	1.09×10^0
CO_2 equiv.	Switzerland	NA	NA	8.75×10^2	NA	7.13×10^0	3.72×10^0	1.59×10^1
	UCPTE	1.34×10^3	1.02×10^3	8.89×10^2	7.72×10^2	8.42×10^0	4.10×10^0	4.95×10^2

[a] Pumped storage not included.

NA = not applicable.

	plants (particularly lifetime extension and increased burnup), use of actual emissions from a modern reprocessing facility, reduced volume of solid wastes;
Hydro systems:	improvements of power plant efficiency (turbine);
PV systems:	improvements of the manufacturing of monocrystalline silicon and amorphous silicon solar cells (yield, electricity consumption) and of the cell efficiencies.

No revolutionary technologies have been considered. Basically, the performance parameters chosen should in most cases be representative for technologies that could be implemented on a large scale between 2010 and 2020. Figure 3 shows the normalized GHG emissions for the advanced coal, gas, nuclear, hydro and PV (roof panels) systems analysed; for the combined gas cycle, an option using oil as an alternative fuel was considered, for reasons of security of supply. The figure indicates the share of GHG emissions originating directly from the plant. As expected, in the case of fossil systems these emissions are dominant, although the contributions from

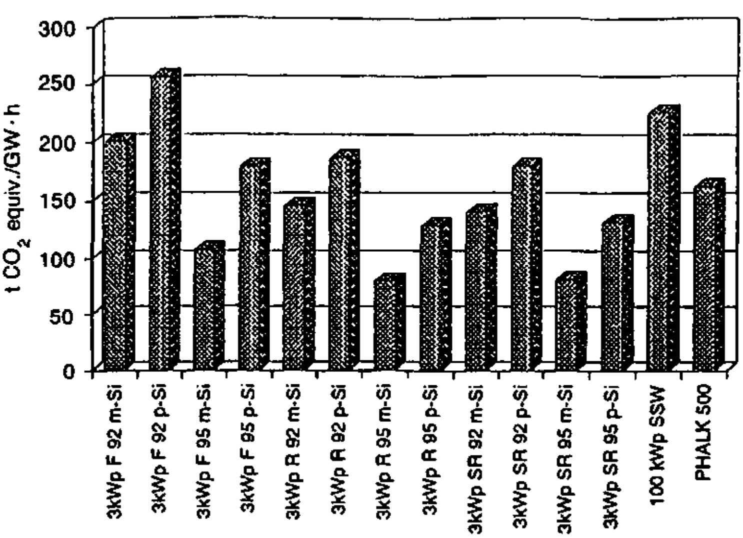


FIG. 2. LCA based GHG emissions from present photovoltaic systems [9] (warming potentials according to IPCC 1992).
3kWp = 3 kW panel; F = façade; R = horizontal roof panel; SR = slanted roof panel; 100 kWp SSW = 100 kW plant near a Swiss highway; PHALK 500 = 500 kW demonstration plant at Mont Soleil, in the Jura Mountains, Switzerland; m = monocrystalline; p = polycrystalline; 92 = technology available in 1992; 95 = expected best technology performance in 1995.

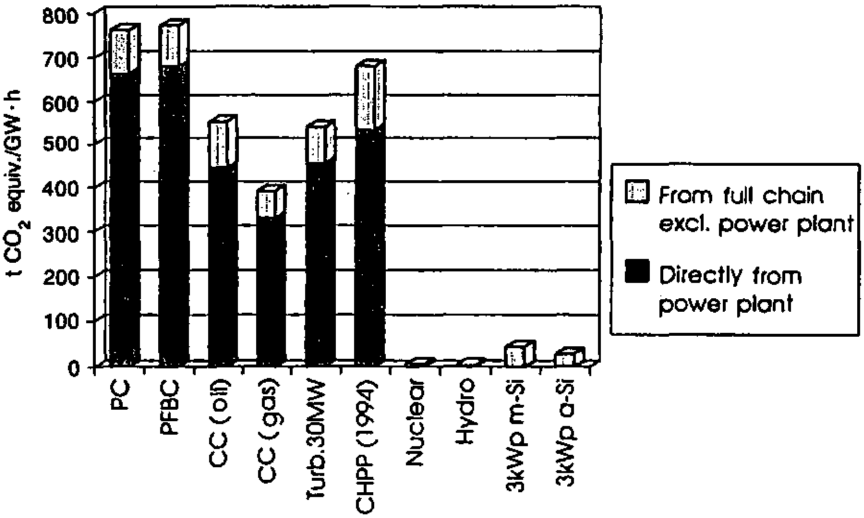


FIG. 3. LCA based GHG emissions from advanced systems [7] (warming potentials according to IPCC 1994).
PC = pulverized combustion (hard coal); PFBC = pressurized fluidized bed combustion (hard coal); CC (oil) = combined cycle (oil); CC (gas) = combined cycle (natural gas); Turb.30MW = gas turbine 30 MW with cogeneration; CHPP (1994) = combined heat and power plant with cogeneration (technology 1994); Nuclear = advanced and simplified light water reactors; Hydro = hydroelectric plants in the Alpine region with increased efficiency; 3kWp m-Si = 3 kW slanted roof panel, monocrystalline Si cells; 3kWp a-Si = 3 kW slanted roof panel, amorphous Si cells.

other steps are not negligible. For fuel cycles other than fossil, the power plants contribute rather insubstantially to the overall result. Generally, in comparison with the currently operating systems (see Table I), GHG emissions are significantly reduced: for gas systems by roughly a factor of two and for PV panels by factors of about two to four when the best current panels are used as reference (otherwise there are higher emissions).

Figure 4 illustrates the emissions of NO_x for advanced cycles. Because of the technological advancements for most systems, the power plant is no longer the dominant contributor. Taking as an example an advanced coal fuel cycle employing pressurized fluidized bed combustion (PFBC) technology and intended for operation in Switzerland around the year 2020, 74% of the total are direct emissions (only 19% of which from the power plant and 68% from transport); the remaining 26% are grey emissions (12% of which is associated with the electricity mix and 88% with materials). For comparison, the share of direct NO_x emissions has been estimated

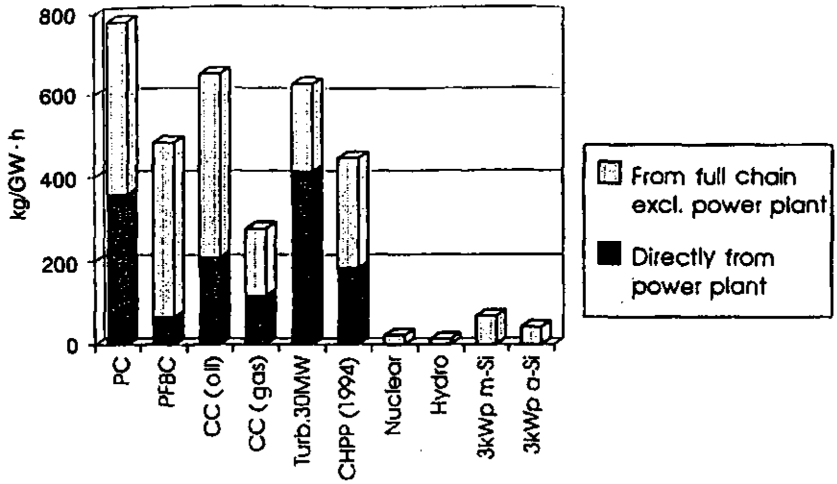


FIG. 4. LCA based NO_x emissions from advanced systems [7] (see Fig. 3).

at 93% for the current coal cycle, based on a modern German PC plant (87% of which from the plant and 9% from transport); the grey emissions are in this case only 7% (32% of which from the electricity mix and 68% from materials).

The study performed demonstrates the feasibility of applying LCA to the electricity supply options for the future, taking into account the technological advancements. Actually, the limitations and uncertainties are considerable. The difficulties concern, for example, scope (choice of the most representative system), appropriate and balanced accounting for technological advancements, and modelling of structural changes (electricity mixes, infrastructure, sources of fuel supply). In spite of these problems, the LCA approach is attractive. In comparison with the traditional focus on the electricity generating plant itself, it provides a much more complete and consistent picture of emissions and residuals associated with the different options and gives a more balanced perspective on the relative importance of the direct emissions from the power plant. While for advanced systems the overall emissions of major pollutants are significantly reduced in the absolute sense, the relative importance of fuel cycle steps other than the plant, as well as of the contributions from transportation and material production, tends to increase. This conclusion can be drawn in spite of the fact that no advancements in the processes for material production and in transportation have been credited. Furthermore, with respect to the major pollutants that have been analysed, the 'ranking' of the different systems is not believed to be distorted by this particular conservatism.

2.3. Current LCA developments towards impact assessment

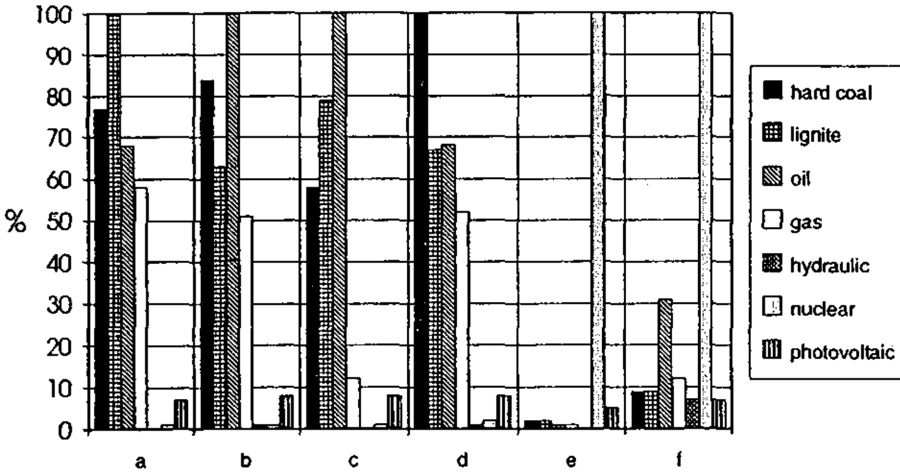
The methodology for the inventory step is very well established. Current developments in LCA are directed at extensions of the basic step towards assessment of impacts [10]. The specific steps are shortly summarized here, followed by an application example and an overview of problem areas.

Characterization. In this step, the different pollutants are aggregated into 13 environmental impact classes, including the greenhouse effect, ozone depletion, acidification, photosmog, nutrification, radioactivity, etc., according to their potential to contribute to the different impacts. In every class, the pollutants are converted into equivalent quantities of a reference substance. For the greenhouse effect, this reference substance is CO_2, and the other GHGs are weighted according to their global warming potential (GWP).

Normalization. Within each class, the contribution of the system (or part of the system) is compared with the worldwide annual emission. Classes where this comparison leads to much lower ratios in relation to the others are considered to have lower priority. Consequently, in the case of power plants, the greenhouse effect, acidification and photosmog have higher priority than nutrification or ozone depletion. Normalization does not aim at a comparison between the overall importance of the different impacts, such as the greenhouse effect, noise or photosmog; this is done within the valuation step.

Valuation. In this step, the overall ecological appreciation of an energy system is provided; thus, the relative importance of the emission of 1 kg of a GHG (such as CO_2) versus the emission of 1 kg of an acidification substance (such as SO_2) or of 1 kg of a nutrification substance (such as phosphate) has to be evaluated. This involves consideration of societal values and preferences and is obviously the most subjective part of the whole process. Examples of methods that have been used in this context are: monetization of the different impacts, approaches based on 'eco-points', and generalized ecological scarcity concepts. The Society for Environmental Toxicity and Atmospheric Chemistry (SETAC) is developing procedural rules for advisory panels of all actors involved in the valuation process; these include: panel composition, interactions with experts, criteria and their hierarchy, and consensus and dissensus rules.

An example of the results obtained for typical current electricity generating systems using the characterization step is shown in Fig. 5 [10]. Some conclusions are:



a	Greenhouse effect	c	Acidification	e	Radioactivity
b	Photosmog	d	Nutrification	f	Land use

FIG. 5. Comparison of different electricity generation systems with respect to various classes of environmental impacts. For every impact class, the most polluting plant type is set to 100% (no normalization is applied here) (see Ref. [10]).

— Hard coal and lignite are most polluting in two impact categories — the greenhouse effect and nutrification; oil is most polluting with respect to photosmog and acidification. These results are sensitive to the quality of coal and oil and the specific cleaning technologies being used (here, average European conditions are reflected).

— For the greenhouse effect, nuclear and hydro are two orders of magnitude better than coal; solar cells are one order of magnitude better than coal and thus less good than hydro and nuclear. This is due to the considerable use of energy for the manufacturing of solar cells (the European UCPTE electricity mix has been used for this calculation; use of the Swiss electricity mix in this context would result in a substantial reduction of GHG emissions allocated to PV systems).

— The relatively large amount of land use for nuclear power systems results from the fact that in the method used, 'land use' also incorporates the time needed for the restoration of the land to the original state, which is very long for the areas used in the context of uranium mining (^{222}Rn emissions from waste ponds are controlled by the parent isotope ^{230}Th, which has a half-life of about 75 000 years). For solar cells the land use is comparatively smaller because of the assumed installation of PV modules (roof panels) on existing buildings, which is the most probable and environmentally favourable installation type for the future.

These conclusions are partially subject to reservations. Impact analyses based on LCA include considerable simplifications and the results exhibit the corresponding limitations. The LCA approach does not distinguish between the physical characteristics of the emissions (e.g. rate, duration, location), meteorological and topographical conditions, complex pollutant interactions and transformations. For example, the results obtained for photosmog are subject to large uncertainties due to the dependences and non-linearities involved. This calls for use of simulation models capable of adequate representation of the prevailing conditions.

3. USE OF SIMULATION MODELS FOR ASSESSMENT OF ENVIRONMENTAL IMPACTS OF AIR POLLUTION

3.1. Objectives and scope

The primary objective is to create a flexible framework and tool for the establishment of correlations between the emission rates of air pollutants originating from the Swiss energy system and the resulting concentrations and impacts for Switzerland, taking into account transport, chemical conversion and deposition. The scope of this work covers the whole energy sector, including electricity generation, heating and transportation. Having in mind the current configuration of the Swiss electricity mix (hydro and nuclear base), the role of electricity within the other components of the energy sector, the drastic reductions of direct emissions of major pollutants from advanced fossil fuelled plants (demonstrated in the LCA) and the spectrum of options considered for the future developments of the power supply, such a broad scope appears necessary. It offers the possibility to provide a proper perspective on the emissions taking place in Switzerland and originating from the electricity supply.

The work aims at simulating the impacts of the future scenarios represented by the different configurations of point, distributed and line sources, using the present situation as the reference case. This differs from the recent external cost studies [3, 4], which had a single plant focus and addressed the present situation only. The rather drastic extension of scope inevitably calls for some reductions in the detail and accuracy of the models used.

3.2. Modelling framework and example simulation

During the past few years, considerable effort has been devoted to the development and application of air quality computer models in order to understand the complicated photochemical processes and to plan efficient emission control strategies (see, for example, Ref. [11]). These models have the capability to predict ozone levels and, to some extent, to simulate the dispersion of other species of interest. While earlier emission control strategies were mainly derived from studies on urban plumes, which usually have limited amounts of volatile organic compounds (VOC), recent strategies focus on the reduction of NO_x in rural environments. This change is based, on the one hand, upon the understanding of the ozone formation processes in air masses moving over rural sites without further NO_x emissions, and, on the other hand, upon the harmful crop losses due to elevated ozone concentrations in these areas. It is essential for the evaluation of control strategies in Switzerland to appropriately represent the photochemical processes, since about half of the area is covered by Alpine mountains without anthropogenic emissions. The thermally driven, daily changing wind system gives rise to an exchange of air masses between the densely populated Swiss Plateau and the Alps.

The three-dimensional urban airshed model (UAM) [12], covering both urban and rural domains, is used for simulations of the atmospheric trace gas concentrations and depositions. Among other inputs the model requires three-dimensional initial concentration fields for all species involved. These fields are usually established on the basis of experimental data. Of interest are the long and short term time evolutions, as well as the horizontal and vertical distributions. Numerous data sources were used for the establishment of the detailed emission inventory for Switzerland, satisfying the requirements of the model; the emissions from the energy sector are being separated from the other emissions, in accordance with the objectives of the present work. The LCA inventory was used as the qualitative reference in this context, as well as for the establishment of priorities with respect to the species to be analysed in detail.

The UAM was initially applied to simulating a summer smog situation in Switzerland [13, 14], using a provisional emission inventory and earlier generated wind fields. Figure 6 shows the calculated ozone concentrations. The highest values (80–85 ppb) were predicted to occur downwind of Zurich. Increased concentrations are also evident in Alpine valleys. The results were found to be in good agreement with airplane measurements over the Swiss Plateau. The highest ozone deposition was predicted for the Alpine regions with high forest coverage. While ozone formation in Switzerland is mainly limited to NO_x, some areas seem also to be sensitive to VOC emissions. According to the calculations, the most efficient way of lowering the ozone levels is to reduce NO_x emissions; controls of VOC emissions are less effective and have an impact over smaller areas.

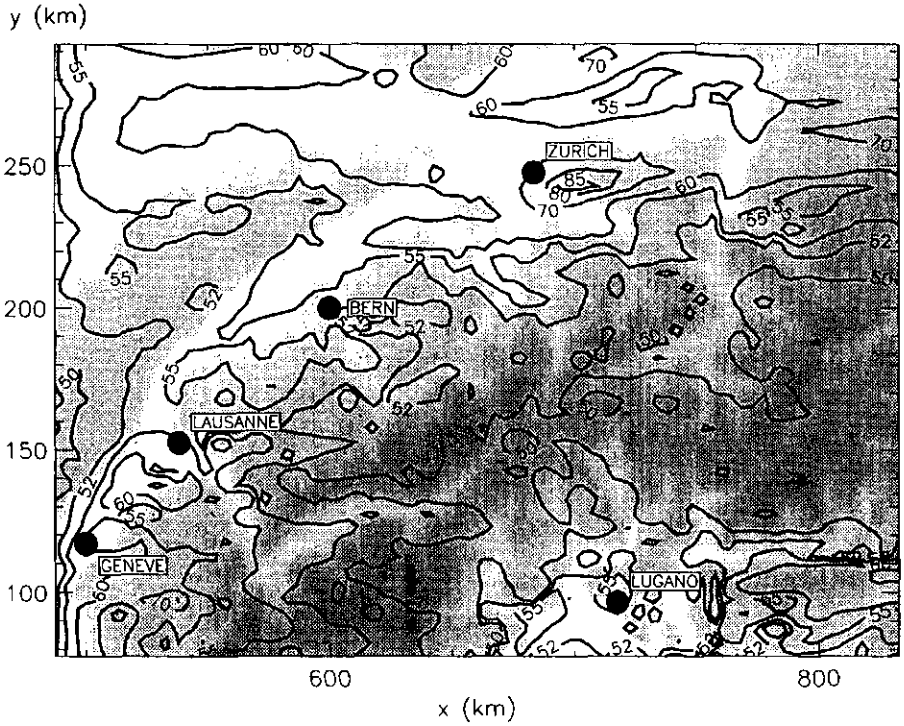


FIG. 6. Average ozone concentrations in ppb (contour lines) between 16:00 and 17:00 CEST, plotted over the Swiss topography (darker regions have higher altitudes) [13].

3.3. Some modelling issues

Some modelling issues associated with the evaluation of the environmental impacts of pollution are intensely debated:

(1) *The accuracy-scope trade-off.* There are two extreme and radically different options for modelling environmental impacts: (a) On a generic basis, by ascribing environmental coefficients to energy resource activities; this does not allow the location specific impacts to be adequately represented. (b) Site specific; this results in a very large volume of work and may be impractical for overall implementation when studying a problem that has such an inclusive scope as the whole Swiss energy system. Clearly, it is necessary to balance between practicality for resource planning and accuracy of environmental impacts.

(2) *Time and space boundaries.* The impact of process boundaries was reflected in LCA. Other researchers have demonstrated that major pollutants are trans-

ported over many hundreds or even thousands of kilometres and that for capturing the major part of the overall impacts it may be necessary to extend the range of the analysis beyond 1000 km. The choice of time boundaries is, to some extent, an ethical issue that is particularly relevant for nuclear waste disposal and for the topic of potential global warming.

In the analyses carried out, different solutions and compromises are being considered with respect to these two groups of issues. For example, criteria have been developed to help to choose between Lagrangian and Eulerian models (such as the UAM) in the context of photochemical air pollution [14]. This has practical implications, since the models have specific advantages and disadvantages, whose importance varies, depending on the problem to be solved. The UAM calculations are time consuming and call for relaxation of the demands regarding the number of cells used and the complexity of windfields. In the Swiss case, transboundary pollution plays a major role. In fact, only 10–15% of oxidized sulphur and oxidized nitrogen deposited in Switzerland are due to emissions in the country itself. Suitable approaches to the treatment of the impacts from the parts of fuel cycles outside Switzerland are being discussed. For practical reasons, these impacts cannot be modelled with the same degree of detail as those for the domestic parts. The modelling options include the use of relevant results from the EC studies [3, 4] on external costs (subject to appropriate adjustments) and/or the use of the earlier described LCA based impact assessment approach for the parts of fuel cycles outside Switzerland.

4. ANALYSIS OF SEVERE ACCIDENTS

The energy sector is considered to be one of the main contributors to man-made disasters. At the same time, major gaps exist in the assessment of the severe accident potential of different energy sources. An attractive analysis approach appears to be a consideration of past accidents, together with uses of PSA techniques. Furthermore, attempts have been made by a number of authors to account for subjective aspects of risk (risk perception) in the context of evaluation of severe accidents.

4.1. Actual experience of severe accidents

A number of existing databases and other sources of information on severe accidents have been identified as primary sources of information. None of the existing sources has been established for the specific purpose of providing comprehensive information about a wide selection of energy systems. In most cases the aim has been to cover natural catastrophes and man-made accidents in general. Consequently, energy related accidents constitute usually a not explicitly identified subset among all other accidents. The WOAD offshore databank is the only exception in this respect. Examination of the different databases showed that major improvements in terms of coverage and quality can be expected as a result of combining the information.

The contents of the existing, available databases, originating from Germany, Norway, Switzerland (insurance), the United Kingdom and the United States of America, were combined by the Paul Scherrer Institute (PSI), and the energy related events were identified. The resulting PSI database focuses on major accidents at fixed installations that store and process hazardous materials, and on accidents that occurred when such materials were transported by road, rail, pipelines, open sea and inland waterways. It should be noted that accidents associated with the transport of persons by road, sea or air are not included.

The information originating from the different sources is partially overlapping. At the same time, there are numerous inconsistencies and contradictions. Furthermore, the overall material is far from complete. For these reasons, other supplementary sources of information are used for checking and identifying additional events. These sources include: annual publications, general and specialized literature, national and international newspapers, incident lists and reports, and direct contacts with responsible companies and other competent organizations/individuals. The process is time and resource consuming; within the present effort, checks and investigations beyond the main sources of information have been concentrated on events that have very severe consequences and/or are subject to major uncertainties with respect to the real extent of consequences.

First evaluations based on the PSI database are reported in Ref. [15]. The database is subject to continuous expansion and revisions. *For these reasons, also the results reported in the present paper should be regarded as preliminary.*

Currently, the PSI database covers 8217 accidents (those associated with person transport are not included); 2289 accidents (27.9%) were classified as energy related; 63.4% of the total are man-made accidents, while 36.6% are natural disasters. Energy related accidents constitute 44.0% of all man-made accidents. For comparison, the commercially available US based Fatal Hazardous Materials Accidents Database has less than 1100 man-made events, of which the energy related accidents are only a subset. This implies that the coverage of energy related accidents has been significantly improved in the PSI database. Figure 7 shows the number of energy related accidents resulting in fatalities for each year between 1945 and 1992, based on the PSI database.

The database contains also records prior to 1945. The coverage is, however, expected to be poor for events that occurred in the distant past. Furthermore, there has been a significant increase in worldwide industrial activities, including the energy related ones. As can be seen from the figure, starting from 1970 there seems to be an increased number of accidents (per year) with at least five fatalities. 80.8% of all accidents in the PSI database occurred in the period 1969–1992. The corresponding number for energy related accidents is 85.2%; in 26.6% of these accidents there were at least five fatalities.

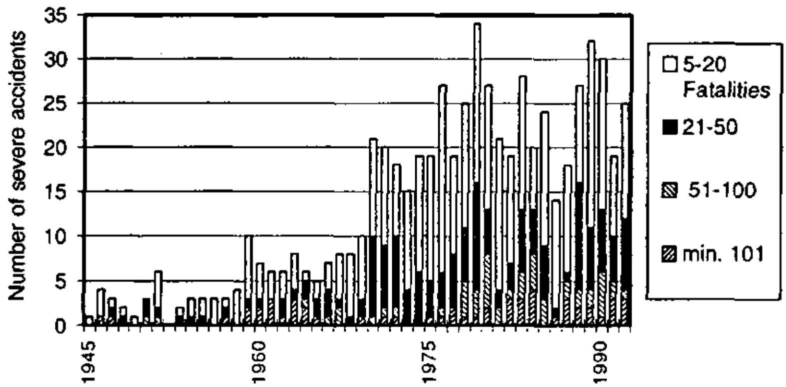


FIG. 7. Energy related accidents leading to different numbers of acute fatalities in the period 1945–1992 (source: PSI database, June 1995).

The combination of information stemming from databases established in different countries appears to provide an improved balance between the reporting levels for individual countries compared with most of the specific sources, which have a tendency of unproportional under-reporting of events that are not domestic.

The completeness of the present database on energy related events can only be addressed qualitatively because of lack of an objective criterion for evaluation. In spite of the progress made, there is reason to believe that events with considerable consequences may still be missing. Besides completeness, reporting accuracy is another problem, which can only be mitigated by the previously mentioned supplementary investigations. Some reasons for the problems regarding completeness and reporting accuracy are: policy decisions in the country of origin, policy decisions on behalf of the receivers of information, commercial confidentiality, military confidentiality, news value, language barriers, lack of knowledge of the actual consequences (especially the indirect ones), and human and organizational factors.

The energy related events in the PSI database were further allocated to the different fuel cycles. The results provided here concern accidents that occurred in the period from 1969 to 1992 and whose consequences were manifested by at least five fatalities. There are specific reasons for choosing these boundaries for the evaluation.

Apart from the already mentioned under-reporting, which is particularly true for events that occurred a long time ago, there are other serious limitations on the use of very old accident records. The susceptibility of energy systems to accidents is subject to temporal changes in many areas such as technological changes, increased hazard awareness, improvements in safety culture and in the efficiency of emergency services, changes in safety regulations and changes in consumer habits. This explains why an evaluation period longer than of the order of 25 years was not chosen for the evaluation. 1969 was selected as the starting year in order to allow some comparisons with the best available previously published corresponding data covering the period 1969–1986 (Ref. [1]; partially from Ref. [16]). When evaluating the events in the severe accident database it would be desirable to cover a wide range of consequences (such as acute and delayed fatalities, serious injuries, evacuation; extensive land, water or food contamination; different types of ecological damages). However, because of scarcity of information, poor statistical evidence and lack of accuracy, only an evaluation of fatalities has been carried out.

Figure 8 shows the number of accidents for the major fuel cycles, based on the PSI database and, for comparison, based on Ref. [1].

Using the data on energy production by different means [17], expressed in terms of equivalent electrical output and the total number of fatalities associated with the accidents shown in Fig. 8, the *immediate* fatality rates were calculated for the different fuel cycles (Fig. 9).

Figures 8 and 9 reflect the better coverage of the PSI database. It can be seen that although the number of accidents from hydro is relatively low, the number of fatalities per event is typically very large, resulting in higher fatality rates. A detailed analysis [18] has shown a large difference between the f–N curves for large dams in Asia and Africa on the one hand and dams in America and Europe on the other

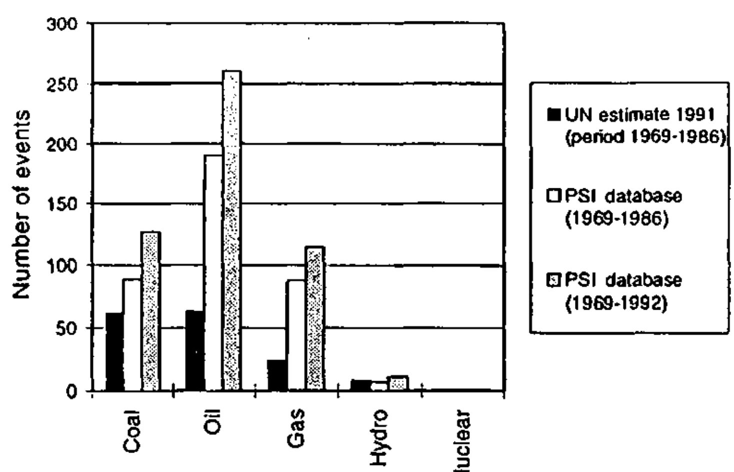


FIG. 8. Comparison of records of energy related severe accidents: total number of events in the examined time periods (source: PSI database, June 1995).

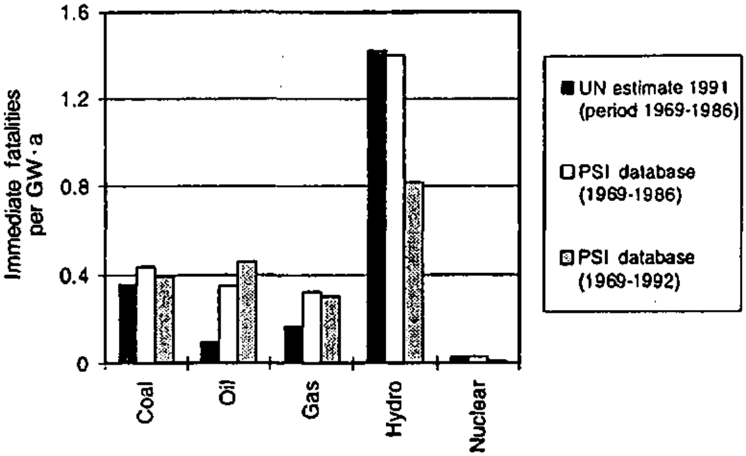


FIG. 9. Comparison of records of energy related severe accidents: immediate *fatality rate per unit of energy (source: PSI database, June 1995).*

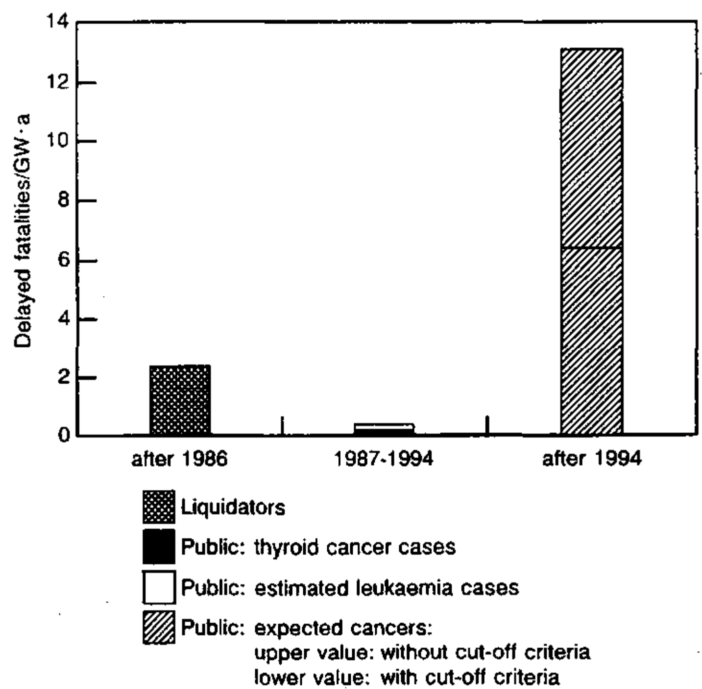


FIG. 10. Delayed *fatalities (per GW(e)·a) estimated for the Chernobyl accident (based on Ref. [19]).*

(the latter show significantly lower risks). For the Swiss dams, in particular, there are some characteristics (dominance of gravity dams, height, capacity, quality of supervision) that have a favourable impact on the estimated dam failure rates. This underlines the need to consider the applicability and transferability of data based on past experience.

Delayed fatalities estimated for the accident at the Chernobyl nuclear power plant are illustrated in Fig. 10 (primarily based on Ref. [19], which in turn uses a number of sources currently considered as the most reliable). The immediate fatalities associated with Chernobyl are included in Fig. 9. For other fuel cycles the potential delayed fatalities due to severe accidents are of a different nature and it is not possible to make an estimate on the basis of the current state of knowledge; however, they are expected to be of secondary importance.

It has to be emphasized that the consequences of the Chernobyl accident shown in Fig. 10 are primarily based on estimates governed by the *assessed* occupational doses (to 'liquidators') and the public doses. This applies fully to the predicted cases of cancer expected to occur in the future and also partially to the results concerning fatalities in the period 1987–1994. For the latter case there are, however, a number of manifested fatal cases of cancer among the 'liquidators' and an excessive number (in comparison with spontaneous incidence) of thyroid cancers among children in Ukraine and Belarus. For latent cancer fatalities after 1994, the impact of using cut-off criteria is demonstrated; the criteria concern dose integration in time (up to 10 years) and space (up to 600 km), and dose magnitude (cut-off at 10 mSv).

Generally, uncertainties are intrinsic to all steps in the evaluation of actual severe accident data. Because of the incompleteness of the available information, the categorization of events as energy related and the allocation to specific fuel cycles involves elements of subjectivity. The most serious problem is the applicability of the data to the current situation in a specific country being subject to energy policy investigations. A screening of the data with respect to inclusion/exclusion of specific countries or regions, taking into account differences in the level of technological development and in the safety culture, may be necessary.

4.2. Application of PSA

PSA provides a structured and logical approach to identifying credible accident sequences, assessing the corresponding likelihood and delineating the associated consequences. One of the important capabilities of PSA lies in the possibility of representing design and site specific features that have a decisive impact on the results of the studies evaluating the potential of severe accidents. Reference [20] provides an overview of the PSA methodology as applied in the study for the Swiss nuclear power plant Mühleberg. For the discussion of PSA limitations, merits and development trends, we refer to Ref. [21].

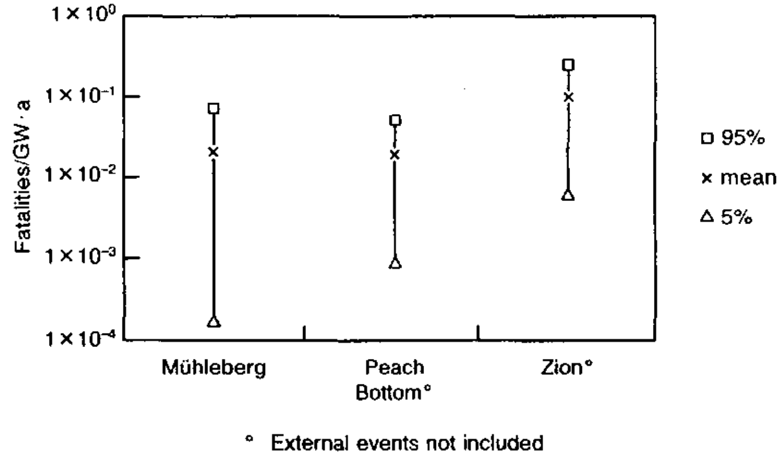


FIG. 11. Estimated latent cancer fatalities due to hypothetical severe accidents (per GW(e)·a) for the Swiss nuclear power plant Mühleberg and two US plants.

Within the GaBE project, the evaluation of severe accidents using probabilistic approaches has until now concentrated on the consequence assessment of hypothetical nuclear accidents, including the associated external costs. Studies of other fuel cycles will follow; a compilation of some representative analyses published before 1989 can be found in Ref. [16].

Figure 11 shows three examples of estimated numbers of latent cancer fatalities per GW(e)·a for the Swiss nuclear power plant Mühleberg and for two US plants, including the associated uncertainty measures (5th and 95th percentiles). The calculated risk measures are based on integration of the full analysed spectrum of accidents. For Mühleberg the contribution of the frequently dominant external events (such as fires, earthquakes, floods, aircraft crashes) is included, while the US studies cover only the internal events. No dose cut-offs were used in the calculations; for the US plants the consequences were calculated for distances up to 1600 km and for Mühleberg up to 800 km.

Several other estimated, normalized risk measures are provided in Ref. [22]. Thus, the mean values for early fatalities (per GW(e)·a) are 10 (Mühleberg) and 6 (Peach Bottom) — three orders of magnitude lower than the corresponding estimates for latent fatalities. For the 'condemned' land area, i.e. the area which cannot be decontaminated before 30 years, the estimates (in km^2 per GW(e)·a) are: 5.9×10^{-3} (Mühleberg), 1.5×10^{-2} (Peach Bottom) and 1.2×10^{-1} (Zion). The large difference between Chernobyl based estimates (Fig. 10) and probabilistic plant specific estimates for Mühleberg and US plants (Fig. 11) illustrates the limitations in the applicability of past accident data to cases that are radically different in terms of technology and operational environment.

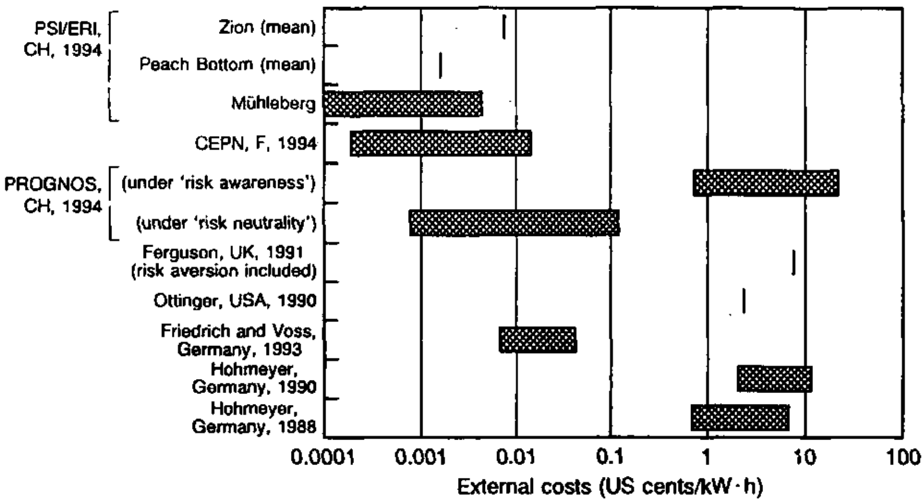


FIG. 12. Span of estimated external costs of severe reactor accidents; the Mühleberg estimate includes external events.

The study performed by PSI in co-operation with Energy Research, Inc. (ERI) extended the consequence analysis for Mühleberg by calculating economic consequences [22]. Three types of costs were modelled: costs resulting from radiation induced health effects, costs from early protective (emergency response) actions and costs from long term protective actions. The results obtained appear to represent the first published attempt to assess external costs for a specific plant, based on a state of the art full scope PSA. The results provided for Peach Bottom and Zion were obtained through elaboration of information from recent studies [23]; as already mentioned, these analyses do not cover external events.

Recently published studies on external costs show differences of several orders of magnitude between the estimated contributions of severe nuclear accidents, leading to the corresponding discrepancies between the overall estimates. Figure 12 illustrates the span of estimated external costs of severe accidents. The reasons for these discrepancies are examined in Ref. [24]. The factors and features having a primary influence on the results are: approaches used for the estimation of the accident frequency and of the magnitude of the consequences, the scope of analysis, the nature of risk integration (in particular accounting for risk aversion) and the economic parameters used.

4.3. Role of aversion to risk

Expert based risk estimates (in our approach equivalent to the application of PSA and appropriately complemented by actuarial data for severe accidents) help to place risks in perspective. However, there is no doubt that a wide gap exists between public perceptions and expert assessment of risks. It has been demonstrated that the influence of subjective aversion to risk on the behaviour of individuals can be significant. Nevertheless, expressed in economic terms (in the context of risk contribution to external costs), the expert approach to the expected damage assumes that money and satisfaction ('utility') are proportionally related. In reality, more money is needed to compensate people for taking risks than the actuarial value of these risks. While this is well understood from a qualitative point of view, the quantification of aversion to risk is subject to controversy. This applies in particular to the issue of integration of aversion to risk when estimating external costs. Most of the available attempts to account for aversion in this context do not inspire much confidence in them and their scientific and empirical bases are weak. Per definition, the aversion factors (i.e. exponents of the magnitude of consequences) are >1 and in most published cases ≤ 2. The consequence of using aversion factors in the high range is that, once the subjective risks are superimposed on the objective ones (obtained as a result of a systematic and transparent process), they tend to overshadow them.

The aversion to specific risks is not homogeneous among the public. In fact, the term 'public' suggests a uniformity of groups, interests, knowledge and concerns; in reality, among the public there is a spectrum of interests, underpinned by a complex array of perceptions, experiences and concerns reflecting psychological, social, cultural and political influences and reactions, all of which are constantly developing and changing [25]. The issue of aversion to risk is in any case important and deserves attention. Extreme nuclear accidents, which potentially could lead to severe land contamination of long duration, would also result in social detriment beyond the quantifiable components of health and economic detriments. In spite of reassuring expert assessments, some people will remain worried about cancers, genetic damage and safety systems that may fail to perform as planned. Perceptions of risk may lead to behaviour that in turn leads to actual costs. It is clear that the public perception of risks must be taken into account in the decision making process (acceptability of technology), but it is a different issue whether and how this aspect should be accounted for when evaluating external costs of energy sources (nuclear as well as others). Methods for quantitative treatment of subjective risks that are better suited than the rather primitive ones employed in some of the widely published past studies are now emerging.

4.4. Current strategy in the analysis of severe accidents

The following points reflect the strategy currently used in dealing with severe accidents in comparative assessment:

— Full energy chains need to be considered in order to ensure that all significant contributions are covered;

— For domestic facilities the applicability of external, historical data needs to be examined;
— For external parts of fuel cycles the proper share of accidents needs to be allocated to the country specific case being investigated;
— For domestic facilities, results based on plant specific PSAs (if available) are most representative.

These principles are in applicable cases consistent with the ones governing LCA, as described in Section 2.

The main problem areas in comparative analysis of severe accidents include:

(a) *Non-uniform level of knowledge and limited scope of applications of risk analysis.* For parts of the different fuel cycles, no analyses are available and/or their quality is at least questionable.
(b) *Difficulties to cover a wide range of consequences in a consistent manner.* Currently, the possibilities of quantitatively assessing for various energy systems the different consequence categories and their likelihood are limited. For this reason, comparisons of quantitative indicators are usually limited to very few categories.
(c) *Treatment of the distribution of impacts in time and space.* Given the increased uncertainty of long range assessments, there is a need to agree on reasonable analysis boundaries that reflect the priorities of decision makers. This issue is relevant also in the context of normal operation.
(d) *Applicability and transferability of data for severe accidents.* Because of technological, operational, cultural and environmental differences, when analysing a specific object, any use of generic or plant specific data (available for a plant other than the one being examined) must take into account these differences. This inevitably involves use of engineering judgement.
(e) *Treatment of aversion to risk and non-quantifiable social detriments associated with extreme accidents.* Further research will hopefully help to improve and balance the current, not very encouraging situation, but it is not expected that this issue will be resolved in the near future.

5. ENERGY ECONOMICS

The primary goal of energy economic studies in the context of integral analysis is to evaluate economic implications of environmental policies. The current focus of such investigations at PSI (as well as at many other research establishments) is on the costs of reducing GHG emissions. Two types of models have traditionally been used for this type of work:

— 'Top-down' economic models analysing aggregated behaviour on the basis of indices of prices and elasticities;
— 'Bottom-up' engineering models focusing on integration of technology costs and performance data.

A recent survey [26] concludes that the estimated costs of reducing emissions span a very wide range. 'Bottom-up' engineering models tend to underestimate costs by ignoring issues associated with implementation and other hidden costs. 'Top-down' economic models, on the other hand, tend to overestimate costs by neglecting the potential for enhancing structural changes and for energy efficiency improvements through regulatory policy. Recent developments have been oriented towards establishing a link between 'bottom-up' and 'top-down' macroeconomic models to describe feedback effects (see, e.g., Ref. [27]). The 'top-down' and 'bottom-up' approaches (or combinations of those) currently used in energy economics disregard market structures and the strategic behaviour of relevant actors. Sector specific studies, on the other hand, examine such aspects and, when used as a complementary approach, have the potential to overcome these shortcomings.

Within the GaBE project, a Swiss specific version of the large scale ('bottom-up') energy-economy model MARKAL is used. The focus of current modelling is on the implementation of the Swiss MARKAL-MACRO model to account for feedback effects [28]. The central development activity is the formulation of a partial equilibrium model and of algorithms for studying 'least cost analysis and demand management', with emphasis on electricity, for Switzerland. The innovative aspect of this method is that it defines the equilibrium between demand and supply as a least cost (optimization) approach. Possibilities to incorporate impact related parameters (possibly in terms of external costs) and material flows within the MARKAL framework are being considered.

The sector specific studies are in the starting phase and will concentrate on conservation options and their sector specific impacts. This activity is expected to bring progress with respect to the evaluation of a realistic energy conservation potential for Switzerland, taking into account that institutional, behavioural and market conditions limit the possibilities and the speed of the realization of energy savings. Some necessary steps in this work include:

— Definition and classification of relevant markets;
— Identification of relevant characteristics of elements acting on these markets;
— Classification of prevailing market structures;
— Formulation of assumptions concerning market behaviour and of hypotheses regarding market co-ordination;
— Empirical verification of hypotheses;
— Sensitivity studies simulating policy impacts.

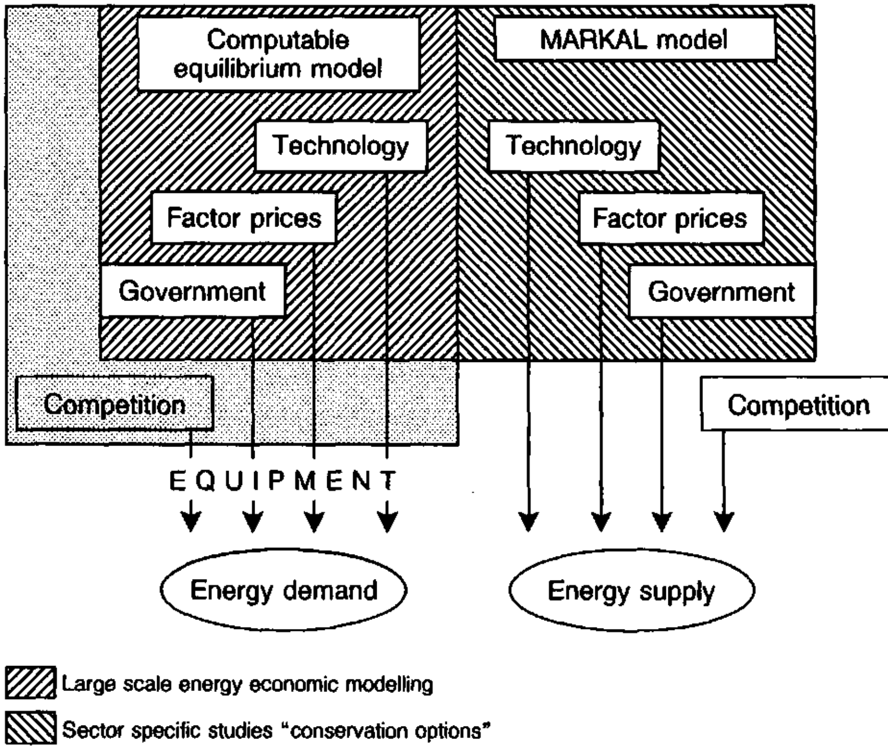


FIG. 13. Overview of the GaBE approach to energy economics.

One or several of quite new paradigms in economics (institutional economics, industrial economics, evolutionary economics, game theory, synergetics, economic theory of law) will be applied here to energy economics and conservation. Figure 13 illustrates the GaBE approach to energy economics.

To a large extent, the work that was carried out using the MARKAL model is a contribution to the IEA/ETSAP project concerning the interrelationships between energy use, emissions to the atmosphere and cost of emission control. As an example, from the results obtained, cost-optimal contributions of the different technologies to reduce CO_2 emissions in Switzerland were calculated for the case of a continued moratorium on nuclear power after the year 2000 and for the 'nuclear available' case; these analyses cover the period until 2025. The detailed results of the Swiss specific applications have been published in Refs [29, 30]. A summary of some representative insights can be found in Ref. [8] and will not be repeated here.

Since Switzerland uses almost exclusively hydro and nuclear for electricity generation, it is not surprising that the estimated costs of GHG reductions are high. As demonstrated within the IEA/ETSAP project [30], this applies to countries such as Norway and Sweden, while more moderate costs are expected for countries that employ fossil fuels to a larger extent for electricity production (such as Japan, the Netherlands and the USA).

The high control costs imply the need of high carbon tax rates. Three options have been studied and found to be efficient for the reduction of the tax level, while striving for fulfilment of the proposal of the Intergovernmental Panel on Climate Change (IPCC) on climatic sustainability [31]:

— Trade-offs between CO_2 and other GHGs.
— Tax compensation payments (proposed by Hediger in Ref. [32]).
— International co-operation [33]. In this example, Belgium, the Netherlands and Switzerland are co-operating in order to reduce their present emissions by 20% by the year 2030. For all co-operating countries the marginal control costs are reduced as compared with unilateral control strategies. The benefit distribution is estimated as: Switzerland 45%, the Netherlands 36% and Belgium 19%.

6. TOWARDS DECISION MAKING

Given the complexity of the problem as well as the diversity of the indicators and interests, the way towards decision making is long and involved. Apart from technical and economic aspects, social preferences need to be considered. The actors participating in the decision making process frequently disagree on the objectives and also on the assumptions made in the treatment of data and/or in analytical methods. Past experience shows that the technical input to the policy debate (some examples of such inputs are provided in this paper) may be deadlocked and that the political process operates in a less informed context [34].

Multicriteria analysis provides a framework that allows the often conflicting socioeconomic and ecological criteria to be addressed simultaneously (see, e.g., Ref. [35]). Actual implementation of such an analysis requires the establishment of a systematic and transparent process, with interactions between analysts and decision makers. Within this process the alternatives and criteria need to be selected and the available immense amount of technical information organized, structured, simplified and reduced. There are various decision making procedures that help to structure the problem and to perform the evaluation in a controlled manner. Two groups of approaches ('decision philosophies') can be distinguished:

(1) The 'platonic' approach assumes that there is a best decision and presupposes that the decision maker has a well established system of values so that he can completely rank any set of events; it is assumed that a majority vote will settle

any dispute. The limitations of this approach include difficulties in the exact specification of the preferences of decision makers, changes in these preferences, aggregation problems, the variety of decision makers, and the fact that decisions are seldom entrusted to a single procedure.

(2) The 'aristotelic' approach intends to eliminate the least satisfactory choices, does not require a complete ranking and looks for a solution for which there is ample support with minimal opposition. This approach aims at constructing a formal system that can help anyone taking part in a decision making process to understand, specify and model his preferences in order to increase the coherence of the process itself.

Which approach is to be used depends essentially on the partners taking the decision. The material to be prepared is in any case fairly the same, independent of which method is the preferred one. Commercial software is available to support both groups of approaches. A representative example for the first group is VISA, a computerized aid to multiple criteria decision making, based upon a simple weighted multiple attribute value function [36]. The second group is supported, for example, by ELECTRE (several versions), which takes into account 'discordance' (i.e. the strongest dissent) and does not yield a complete ranking of alternatives [37].

Examples of successful applications of multicriteria analyses are available and have been applied at local and regional levels (in the context of electricity supply, see, e.g., Ref. [34]). The feasibility of such approaches for extensions to the level of national energy policy planning needs to be examined. While it would be naive to believe that a definite and wide consensus could be reached on the basis of this type of procedure, the merits of the underlying systematic and informative process to support future decisions make it worth trying.

7. CONCLUDING REMARKS

The present paper provided an overview of the analysis framework established in Switzerland for comparative assessment of energy systems. Examples of results obtained to date were given to illustrate the progress achieved as well as to underline current issues in areas such as completeness and depth of databases, analysis boundaries, environmental impact assessment, treatment of severe accidents, and accounting for technological advancements. In view of the need to integrate results to support the decision making process, some options that could be used in this context were briefly outlined.

With the exception of severe accidents, the external costs of power generation were not extensively addressed in this paper, particularly in view of the fact that other contributions to this Symposium concentrate on this topic. Estimation of external costs can be viewed as an integrative approach, since the diverse impacts are expressed in common (monetary) units. At the same time, non-quantifiable aspects that may be of large importance are not accounted for when estimating external costs. Furthermore, current external cost analyses have a focus on single plants and concern only present technologies. It is worth noting that when the best present operating technologies are considered, the estimated environmental external costs according to recent studies tend to be relatively small, with reservation for the potential contribution of aversion to severe accidents (discussed in this paper), and it is extremely difficult to assess the impacts of global warming. The framework described in this paper definitely does not exclude the use of external costs as an integrative indicator when comparing the different options. In fact, efforts were made within our work to advance the treatment of some controversial aspects such as the assessment of external costs associated with severe accidents. The ambition is, however, to aim at a scenario based representation of the options and, consequently, at modelling the overall energy system rather than focusing on one specific plant at a specific location. Having this goal, accuracy-scope trade-offs are inevitable and are being continuously considered in the course of this work.

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LIFE CYCLE ANALYSIS OF ELECTRICITY GENERATION AND SUPPLY SYSTEMS
Net energy analysis and greenhouse gas emissions

Y. UCHIYAMA
Technical Assessment Group,
Socioeconomic Research Centre,
Central Research Institute of the Electric Power Industry,
Tokyo, Japan

Abstract

LIFE CYCLE ANALYSIS OF ELECTRICITY GENERATION AND SUPPLY SYSTEMS: NET ENERGY ANALYSIS AND GREENHOUSE GAS EMISSIONS.

A study has been performed with the aim of developing a method of environmental inventory analysis for the full energy chain of electricity generation and supply systems, using the life cycle analysis methodology, and constructing a comprehensive database for applications in Japanese electric utilities. The net energy analysis and greenhouse gas emissions are investigated for the total electricity generation and supply systems of fossil, nuclear and renewable energy sources, including extraction, processing and transportation of fuel, power generation, transmission, distribution, plant dismantling and waste disposal. Production of materials, manufacturing of equipment and site construction are also evaluated, as well as operation and maintenance of plant facilities in the full energy chain. Both conventional and advanced generation technologies are investigated in the study.

1. INTRODUCTION

In order to reduce CO_2 emissions from electric utilities in the future, it is necessary to develop energy conservation technologies, the use of non-fossil fuels such as nuclear and renewable energy, and CO_2 removal technologies. To make visible the effects of environmental technologies, they must be reviewed in detail to evaluate their possibilities. Life cycle analysis is one of a number of useful methods to analyse greenhouse gas (GHG) emissions from energy supply systems. This method is based on the inventory analysis of net energy completed during the 1970s [1–3]. The main goal of the inventory analysis is to determine the magnitude of the relevant inputs and outputs of certain electricity supply systems.

We have developed a methodology of life cycle analysis to evaluate the net energy requirements and the GHG emissions for the total electricity supply system, ranging from the extraction of energy resources through processing, power generation, transmission and distribution, to dismantling of facilities and disposal of waste.

Our previous reports on net energy analysis and CO_2 emissions of various electricity supply technologies were published between 1991 and 1994 [4–7]. This paper, which is based on the above reports, presents a further analysis of the effect of transmission and distribution of electricity and the advanced technologies.

2. METHODOLOGY

2.1. Net energy analysis

The life cycle analysis applied in this study is an approach using a combination of process analysis and the Japanese input–output table. Each energy system is subdivided into the energy chain processes of fuel extraction, transportation, treatment, conversion and waste disposal. A bottom-up process chain methodology is used for the calculation of energy balances for these processes. All processes are described on a 'cradle-to-grave' basis. Energy and material requirements are calculated in the process analysis for all stages of plant construction, operation and maintenance (O&M) and dismantling for the duration of each process. The energy consumption of material production is calculated with the Japanese input–output table (1990) adjusted by adding the energy for the transportation of ores imported from foreign countries and the energy required for the assumed aluminium production in Japan.

The input energy of an electricity supply system is the total life cycle energy, i.e. the sum of the energy required for plant construction, including production of materials and equipment, and the operational energy consumed in all processes of the system. The output energy of an electricity supply system is the total amount of electricity produced or supplied to consumers during the plant life.

The energy ratio is defined as the electrical output divided by the equivalent electrical input:

$$\text{Energy ratio} = \text{out}/(\text{in}_t/\alpha + \text{in}_e$$

where out is the electrical output, in_t is the thermal input, in_e is the electrical input and α is the conversion factor of electricity to primary energy (9.42 MJ/kW·h).

2.2. Analysis of GHG emission

Using net energy analysis, the life cycle CO_2 emission is derived from the direct emissions from combustion of fossil fuelled power plants and the indirect emissions associated with the energy consumed for construction and O&M of the electricity supply system. The study also includes methane gas leakages during mining of coal or extraction of natural gas and the CO_2 emissions from cement production. Methane is one of the greenhouse gases; it has a global warming potential that is 21 times higher than that of CO_2 for a time horizon of 100 years. The greenhouse effect of an electricity supply system is expressed in terms of a CO_2 emission factor. This factor can be calculated by the following equation:

$$CO_2 \text{ emission factor} = (E_1 + E_2 + E_3 + E_4)/\text{out}$$

where $E_1 + E_2 + E_3 + E_4$ is the total CO_2 emission from an electricity supply system during the plant life, E_1 is the direct emission from fossil fuel combustion at a power plant, E_2 is the indirect emission from construction and O&M, E_3 is the indirect emission from cement production and E_4 is the equivalent CO_2 emission from methane leakage.

3. ELECTRICITY SYSTEMS

3.1. Conventional electricity systems

Life cycle analysis focuses on the sequence of fuel extraction, transportation, treatment, conversion, transmission and distribution, waste disposal and dismantling

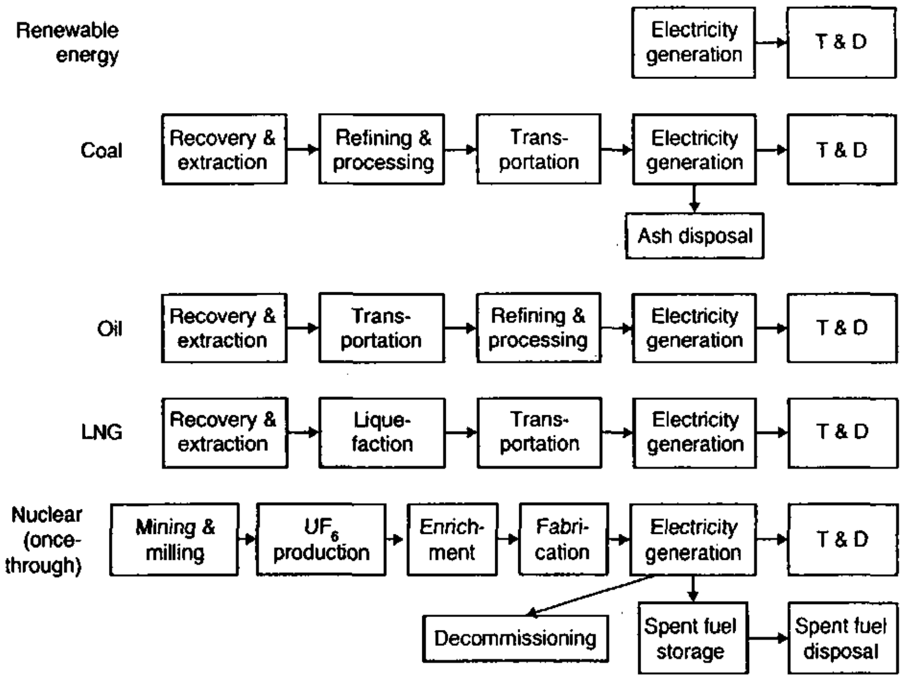

FIG. 1. Scope of fuel chain processes of electricity supply systems.

TABLE I. EVALUATED ELECTRICITY GENERATION SYSTEMS

Option	Gross capacity (MW)	Capacity factor (%)	Net efficiency (%HHV)	Remarks
Coal	1000	75	36.1	Pulv. coal, SO_x/NO_x control
Oil	1000	75	36.6	Heavy oil (C)
LNG[a]	1000	75	37.6	
Nuclear	1000	75	32.4	BWR, burnup: 30 000 MW·d/t U
Hydro	10	45		Head: 250 m, max. flow: 4.8 m^3/s
Geothermal	55	60		Double-flash type
Wind	0.1	20		Propeller type, downwind
Wave	1	25		Floating type
Tidal flow	3	40		Rotor type mill
OTEC[b]	2.5	80		Binary cycle, depth 700 m
Solar th. PV[c]	5	30		Tower type
Utility	1	15		Polycrystal, syst. eff. 11%
Roof top	0.003	15		Polycrystal, syst. eff. 12%

[a] Liquefied natural gas.
[b] Ocean thermal energy conversion.
[c] Solar thermal photovoltaic.

TABLE II. MATERIAL REQUIREMENTS FOR ELECTRICITY LINES FOR POWER PLANTS

	Nuclear		Fossil fuels		Hydro
	Remote site	Local site	LNG	Oil	
Capacity (MW)	9096	2200	5600	3200	254
Distance (km)	447.7	273.4	270	150	28.00
Materials (kg/kW·km)					
Steel	14.95	36.86	15.69	14.43	9.59
Copper	0.25	0.42	0.34	0.23	0.102
Aluminium	3.49	8.42	4.00	3.37	2.43
Concrete	110.41	266.02	126.20	107.39	94.72
Ceramics	2.54	6.00	2.74	2.43	1.07
Glass	0.0014	0.0035	0.0019	0.0018	0.0039

TABLE III. ADVANCED POWER GENERATION TECHNOLOGIES

Technology	Characteristics	Gross efficiency
Advanced LNG combined cycle	Gas turbine: 1350°C	48% (HHV)
Ultra-supercritical coal fired	Steam: 351 atm (abs.), 649/595°C	40% (HHV)
Integrated gasification combined cycle (IGCC)	Gasifier: dry coal, air blown Dry gas cleanup, G/T: 1300°C	42% (HHV)
IGCC fuel cell	Gasifier: dry coal, air blown Dry gas cleanup Molten carbonate fuel cell	52% (HHV)
Fuel cell cogeneration	Phosphoric acid, 5 MW(e)	39% (HHV) 80% (total)
CO_2 recovery (coal)	O_2/CO_2 burning, 90% removal	29% (HHV)
CO_2 recovery (LNG)	PSA process, 90% removal	34% (HHV)
Fast breeder reactor	Metal fuel, co-reprocessing	36%
Photovoltaic cell	Roof top, 3 kW_p	
PV-1	Polysilicon, 1 GW/a, 300 μm thick	20% (cell eff.)
PV-2	Polysilicon, 1 GW/a, 150 μm thick	20% (cell eff.)
PV-3	Amorphous silicon, 1 GW/a	12.6% (cell eff.)

of the facility. Figure 1 shows the scope of fuel chain processes of different electricity supply systems, which can be divided into three main components: upstream, conversion and downstream.

Table I shows the commercially available and the near-commercial electricity generation systems treated in this study. These systems use fossil fuels, as well as nuclear and renewable energy sources and have an industrial scale of output. Generally, conventional fossil fuelled and nuclear power plants have a gross output capacity of 1000 MW(e) and a capacity factor of 75%. The capacity factors of technologies using renewable energy sources are the best values achieved in Japan. Fossil fuels are imported from foreign countries, such as Australia and China, and countries in the Middle East and in South Asia. The nuclear energy chain covers various fuel processes of the once-through type or the plutonium recycle type. Uranium enrichment of UF_6 is performed with the conventional gas diffusion process for the once-through system and the centrifugal process for the plutonium recycle system.

Life cycle analysis of the transmission and distribution system has been performed by investigating the electricity generation mix in the Tokyo district. Hydro, nuclear, LNG and oil power stations are connected by local trunk lines, which are connected with the distribution network in the urban area. Table II presents the material requirements for electricity lines for power plants.

3.2. Advanced electricity systems

Efficient energy utilization by means of advanced high-efficiency power plants and cogeneration systems is a significant R&D issue, with the aim of improving the energy ratio and reducing CO_2 emission from fossil fuelled power plants. Table III gives the performance characteristics of advanced fossil fuelled power plants that are expected to be installed in the future. The advanced LNG combined system, the ultra-supercritical (USC) system and phosphoric acid cogeneration will be used in the near future. The gross efficiencies given in Table III for the integrated gasification combined cycle (IGCC) and the molten carbonate fuel cell are target values.

The effect of CO_2 recovery systems in fossil fuelled power plants is investigated in the study. Among several CO_2 recovery systems under development, two near-commercial processes with high efficiency are investigated: the pressure swing adsorption process for LNG fired plants and the O_2/CO_2 burning process for coal fired plants. The CO_2 recovered is compressed and liquefied after separation from the exhaust gas of a power plant, and the liquefied CO_2 is transported by a tanker to a disposal site. A floating type discharge platform is assumed to be located 3000 km away from the power plant. From this platform the liquefied CO_2 is dumped into the ocean to a depth of 3000 m using a vertical steel pipe.

The effect of a fast breeder reactor (FBR) is also investigated in the study. The FBR investigated has an advanced technology with a power output of 1000 MW(e) and uses metal uranium fuel reprocessed at the site of the plant.

The solar PV system consists of a large number of solar cells. Manufacturing of such systems requires process materials such as high quality silicon and aluminium, which are very electricity intensive materials. The energy ratio and the CO_2 emission factor of solar PV systems could be improved if thin silicon cells with higher efficiency were to be developed.

4. RESULTS

4.1. Net energy analysis

4.1.1. Conventional electricity systems

Figure 2 shows the energy ratios of conventional electricity generation systems, without transmission and distribution, assuming an equipment life of

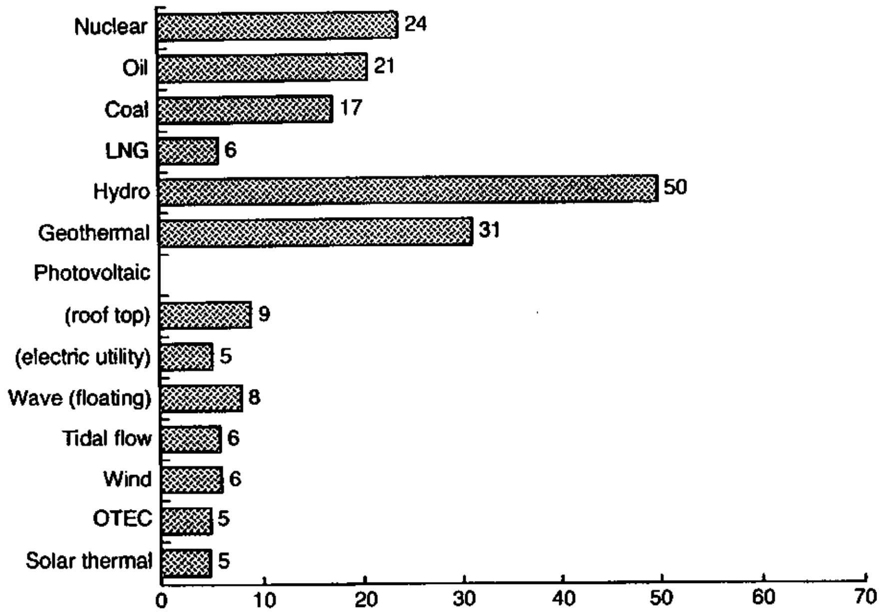

FIG. 2. Energy ratio of electricity generation systems (without T&D).

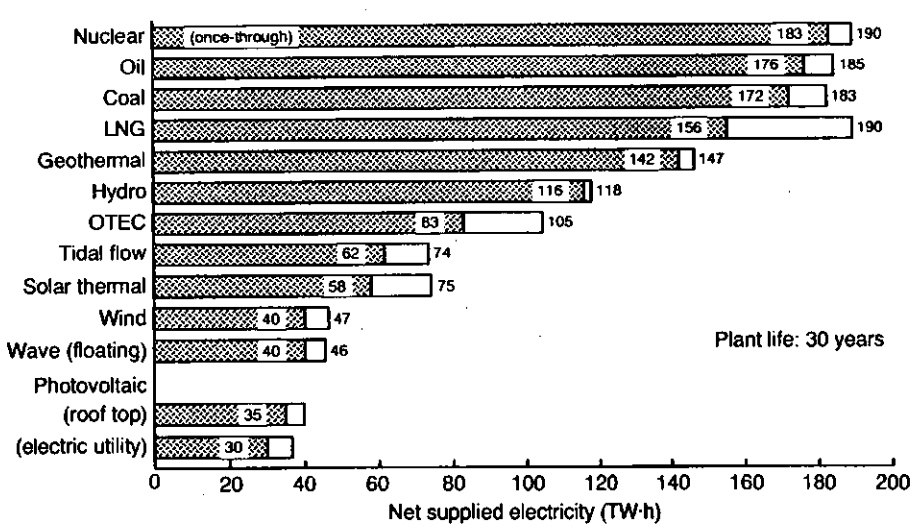

FIG. 3. Net electricity supplied by electricity generation systems (1000 MW).

TABLE IV. ENERGY RATIO AND TOTAL EFFICIENCY OF ELECTRICITY SUPPLY SYSTEMS INCLUDING T&D IN THE TOKYO DISTRICT

	Nuclear		Fossil fuels			Hydro
	Remote site	Local site	LNG	Oil	Coal	
Capacity (MW)	11 140	2200	19 450	9440	1670	11 670
Capacity factor (%)	70.7	70.7	56.7	46.5	69.1	19.0
Net efficiency (%)	32.01	32.01	37.63	37.16	35.60	—
Net supply (TW·h)	68.99	13.63	96.61	38.45	10.11	19.44
T&D loss (%)	11.4	8.2	7.5	5.9	8.2	11.4
Final supply (TW·h)	61.13	12.51	89.36	36.18	9.28	17.22
Input energy (TJ/a)	14 446	2985	213 256	28 585	6224	13 231
Generation	(12 005)	(2370)	(207 371)	(26 524)	(5761)	(10 819)
T&D	(2 441)	(615)	(5 885)	(2 061)	(463)	(2 412)
Energy ratio	39.9	39.5	3.95	11.9	14	12.3
(without T&D)	(54.1)	(54.1)	(4.39)	(13.6)	(16.5)	(16.9)
Total efficiency (%)	27.84	28.83	28.28	32.47	30.81	—
Efficiency loss (%)	4.17	3.18	9.35	4.69	4.79	—

30 years. Clearly, the energy ratio of each technology is more than unity, which is required for an energy technology to be a producer of net energy.

Hydro, geothermal, nuclear, oil and coal fired power systems have excellent energy ratios because of their higher energy density and capacity factor. The energy ratio of LNG fired power plants is only one third of that of other fossil fuelled plants because a large amount of energy (10–15% of the natural gas produced) is consumed during extraction and liquefaction. The energy ratios of renewable energy sources, except hydro and geothermal, are less than ten because of their lower energy densities.

Figure 3 shows the net electricity supplied by different systems with a gross power output of 1000 MW(e) and a plant life of over 30 years. The value of the net supplied energy depends strongly on the capacity factor of a power plant. The higher the capacity factor, the more electricity is produced. The average capacity factor of PV systems in Japan is below 15%, which is much smaller than that of nuclear and fossil fuelled power plants (75%). Therefore, the net energy supplied by a nuclear system is six times higher than that of a PV system, as shown in the figure. Although the energy ratio of the LNG fired system is low, the net supplied energy is higher than that of hydro and geothermal systems because of its higher capacity factor.

When the effect of transmission and distribution of electricity is taken into account in the calculation of the net energy, the energy ratio of electricity supply systems could be decreased because of the loss of electricity during power transmission and the energy requirements for construction of transmission and distribution (T&D) facilities. Table IV shows the energy ratio and the total efficiency of the T&D system in the service area of the Tokyo district. There seems to be a large decrease in the energy ratio; this is mainly caused by the low values of the actual capacity factor and the relatively high energy loss during power transmission. The total efficiency can be calculated as follows:

$$\text{Total efficiency} = 3600 \times \text{final supply (TW·h)}/(3.6 \times 8.76 \times \text{capacity (MW)} \times \text{capacity factor/net efficiency} + \text{input (TJ)})$$

The largest decrease in the energy ratio occurs in hydropower plants because of the extremely low capacity factor of 19% and the high energy loss during power transmission. Regarding nuclear power plants, the long transmission line to remotely located plants leads to a drop of the energy ratio.

4.1.2. *Advanced generation technologies*

Efficient energy utilization by means of advanced high efficiency power plants and cogeneration systems is a significant R&D issue with the aim of improving the energy ratio. Figure 4 shows the energy ratio of advanced electricity supply systems. The energy ratio increases in proportion to the higher thermal efficiency of advanced

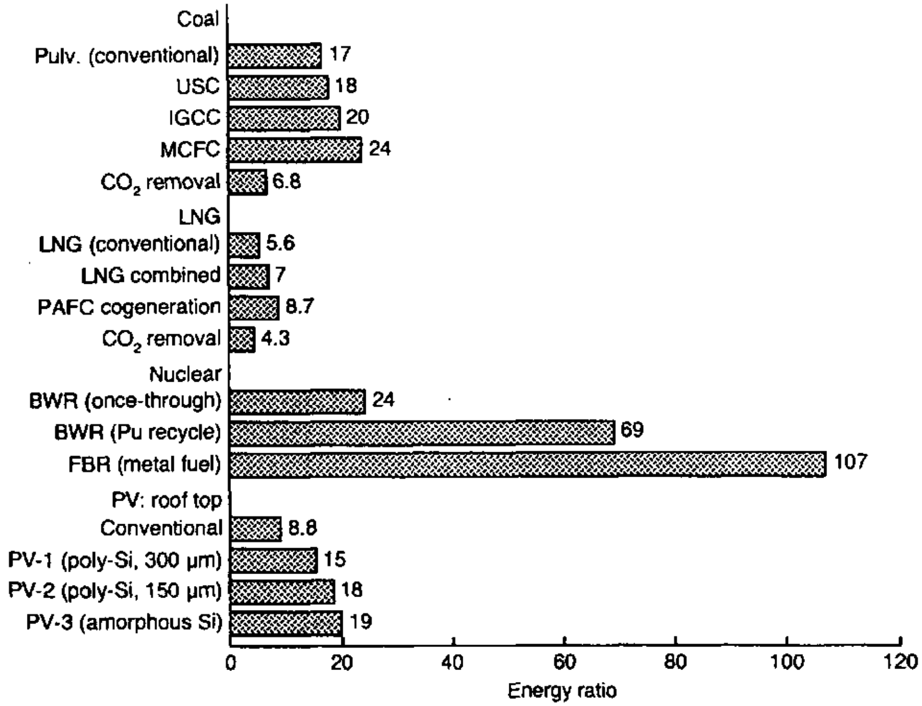

FIG. 4. Energy ratio of advanced electricity supply systems.

fossil fuelled power plants including cogeneration. The CO_2 removal process in fossil fuelled power plants could reduce the CO_2 emission from the plant, but it could lead to a decrease in the energy ratio because a large amount of energy is consumed for plant operation.

The energy ratio of nuclear systems is highly affected by the uranium enrichment process. The gas centrifugal enrichment process contributes to an improvement of the energy ratio, which becomes 24 for the gaseous diffusion process and 76 for the centrifuge process. In the FBR the energy ratio is also improved because there is no uranium enrichment process: it is four times higher than that of a BWR with gaseous diffusion.

The energy ratio of a PV system can be improved if the PV panels are installed on the top of the roof because in this case no PV module frames, etc. have to be fabricated. Development of a new silicon cell with high performance could also lead to an increase in the energy ratio. This would be two times higher than that of the conventional PV system.

4.2. Greenhouse gas emissions

4.2.1. Conventional power generation technologies

Figure 5 shows the CO_2 emission factor, including methane leakages, for conventional electricity generation systems. Obviously, nuclear, hydro and geothermal systems, which attain a high energy ratio, are systems with low CO_2 emissions. Fossil fuelled plants release a large quantity of CO_2 — 31–47 times more than nuclear power systems. The CO_2 emissions per kW·h of plants with solar thermal, PV, wave, OTEC, tidal flow and wind power technologies are smaller than those of fossil fuel systems, but they are one order of magnitude larger than those of nuclear systems.

Fossil fuelled plants have an extremely high CO_2 emission per kW·h because of the large quantities of CO_2 emitted during fuel combustion. The direct CO_2 emissions from fossil fuelled plants are 10–20 times higher than the indirect emissions associated with the total energy requirements for plant construction and operation during a plant life. The CO_2 emission factors of fossil fuelled plants exceed the average value of 128 g C/kW·h calculated for the Japanese power generation mix in 1992.

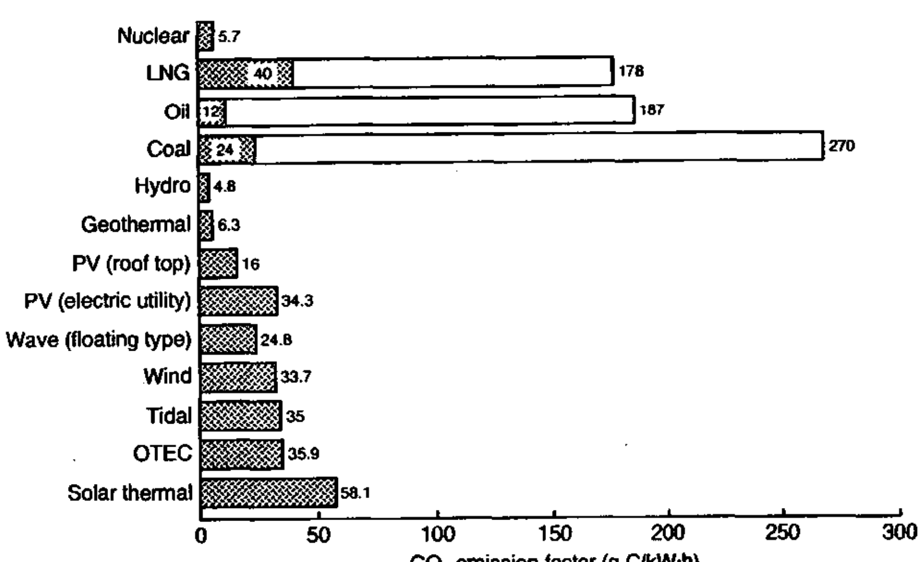

FIG. 5. Greenhouse gas emission factor of different electricity generation systems.

4.2.2. Advanced generation technologies

On the basis of the performance characteristics given in Table III, the CO_2 emission factors of advanced technologies have been calculated. Regarding fossil fuelled power plants, the CO_2 emission factors decrease in proportion to the thermal efficiency of a plant. The CO_2 emission factor of fossil fuelled power plants could decrease with the installation of a CO_2 removal facility. However, the effect is 73% for coal plants and 63% for LNG plants even though the CO_2 removal rate from flue gas is 90%. This is due to the large drop of the thermal efficiency, i.e. a large quantity of electricity is consumed as auxiliary power for the CO_2 removal plant.

The CO_2 emission is much improved by installing an advanced nuclear fuel cycle with centrifuge enrichment and an advanced fast breeder reactor. The emission factors of the advanced technologies are less than half of the conventional values. The CO_2 emission factor of a PV system could be improved if a higher efficiency PV cell were to be developed. As shown in Fig. 6, the use of advanced PV cells, such as a thinner silicon cell and an amorphous silicon cell with higher efficiency, could reduce the CO_2 emission factor by up to half of that for conventional cells in the case of roof-top installation.

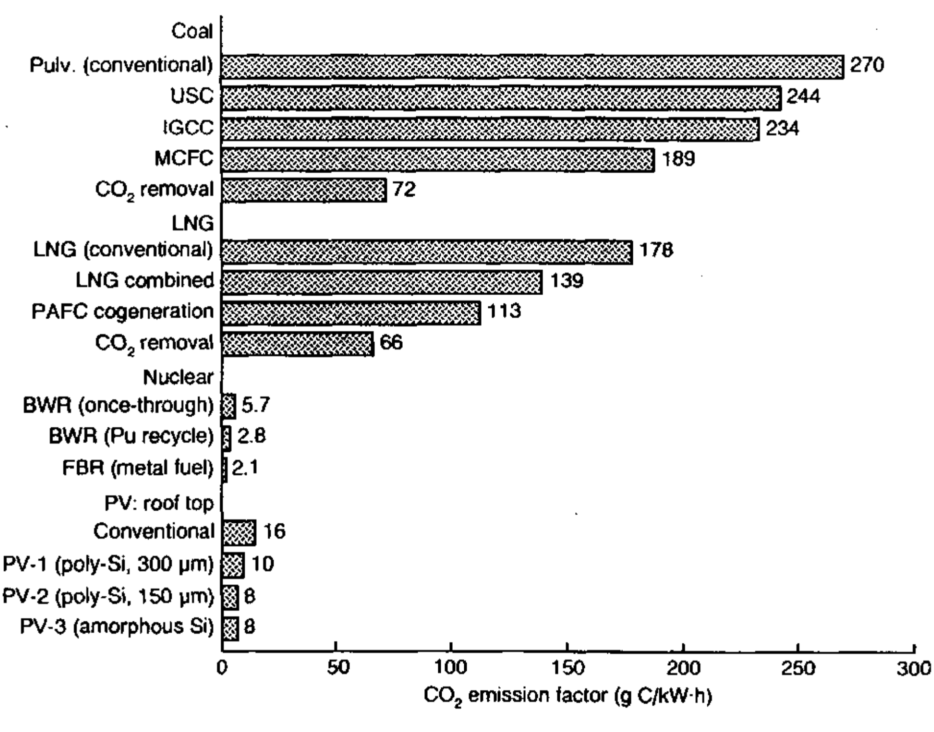

FIG. 6. CO_2 emission factor of advanced electricity supply systems.

5. CONCLUSIONS

The study presents the Japanese results on net energy and GHG emissions of various electricity supply systems, using the life cycle analysis of the full fuel chain. The results can be used by decision makers in evaluating the CO_2 reduction options of different electricity generation systems.

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ENERGY CHAIN ANALYSIS FOR COMPARATIVE ASSESSMENT IN THE POWER SECTOR

I.F. VLADU
Planning and Economic Studies Section,
Division of Nuclear Power,
International Atomic Energy Agency,
Vienna

Abstract

ENERGY CHAIN ANALYSIS FOR COMPARATIVE ASSESSMENT IN THE POWER SECTOR.

The paper presents the results obtained in constructing and implementing a general framework for comprehensive comparative assessment within the inter-agency joint project on databases and methodologies for comparative assessment of different energy sources for electricity generation (DECADES). A short description of the DECADES project structure and the main components is given. The technology inventory databases, which are a major part of the project, address all levels of different energy chains, from fuel extraction through electricity generation to waste disposal. The concept and content of the reference technology database (RTDB) are introduced, and the present status and planned future developments are described in the paper. The database supports comparative assessment in the power sector, by providing generic information about existing energy technologies and technologies expected to enter the market in the next two to three decades. The data collection, review, consistency checking, update and maintenance process is presented, and summaries of technical, environmental and economic characteristics of principal electricity generating technologies are given. Information on several typical facilities is given, illustrating the possibilities to store numerical, textual and pictorial information in the database structure. Specific information to be used in country studies is provided in the DECADES project by country specific databases (CSDBs). The CSDBs, following the structure of the RTDB, supplemented with data specific to electricity systems, have been established by some 15 countries, and example results illustrating specific situations and requirements are presented. The paper also presents preliminary results, showing the types of comparative assessment that can be carried out using the methodology and databases developed. In this connection, the possibilities and limitations of energy chain analysis are introduced and the differences with regard to life cycle analysis methodologies are discussed. Specific features of energy chains used in different countries are also addressed and typical chains are presented. Finally, the DECPAC model is described, showing its capabilities for modelling the complete electricity generation system, with a mix of energy chains, for a given country or region. The DECPAC model extracts data from the RTDB or CSDBs, performs an economic optimization of the generation system expansion plan, and provides reports on the costs, emissions and other environmental burdens for the optimized expansion plan. Experience has already been gained on the use of the databases and the DECPAC model developed by the DECADES project. This shows that these tools would be very useful for countries wishing to carry out comprehensive assessment of different options for meeting their future electricity demands.

1. INTRODUCTION

The inter-agency joint project on databases and methodologies for comparative assessment of different energy sources for electricity generation (DECADES) was established with the objective of enhancing the capabilities for incorporating health and environmental issues in the comparative assessment of different electricity generation chains and strategies in the process of planning and decision making for the electricity sector. Figure 1 gives a schematic overview of the main elements of comparative assessment of electricity generation chains for planning and decision making, and indicates the scope and the boundaries of the DECADES project within this framework.

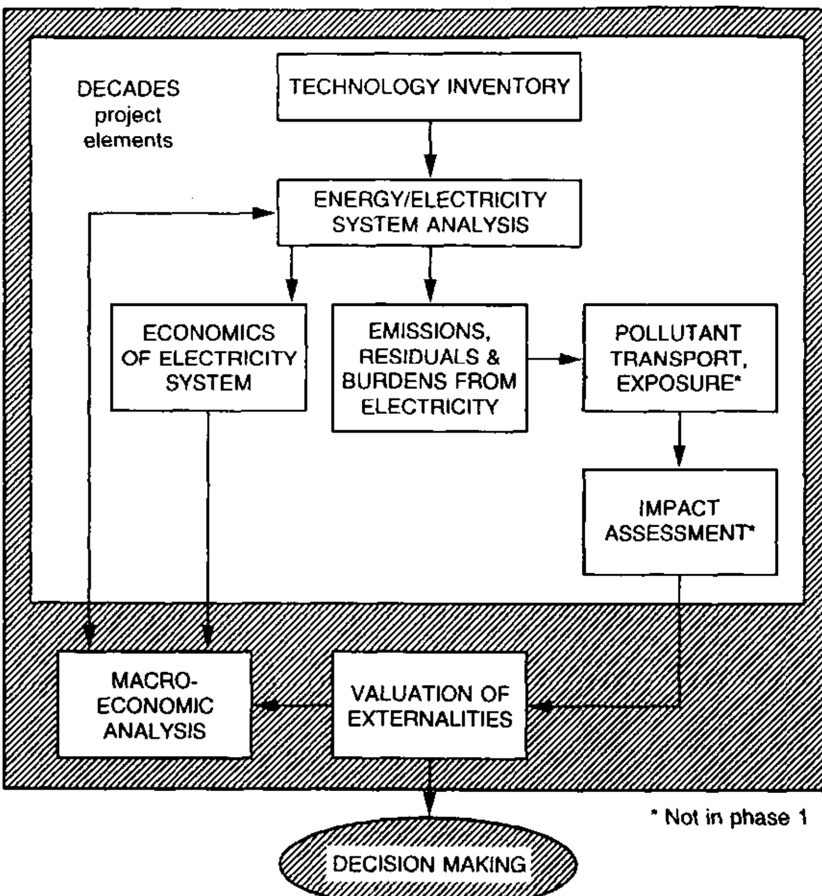

FIG. 1. The DECADES project coverage in the overall framework of comparative assessment for decision making in the electricity sector [1].

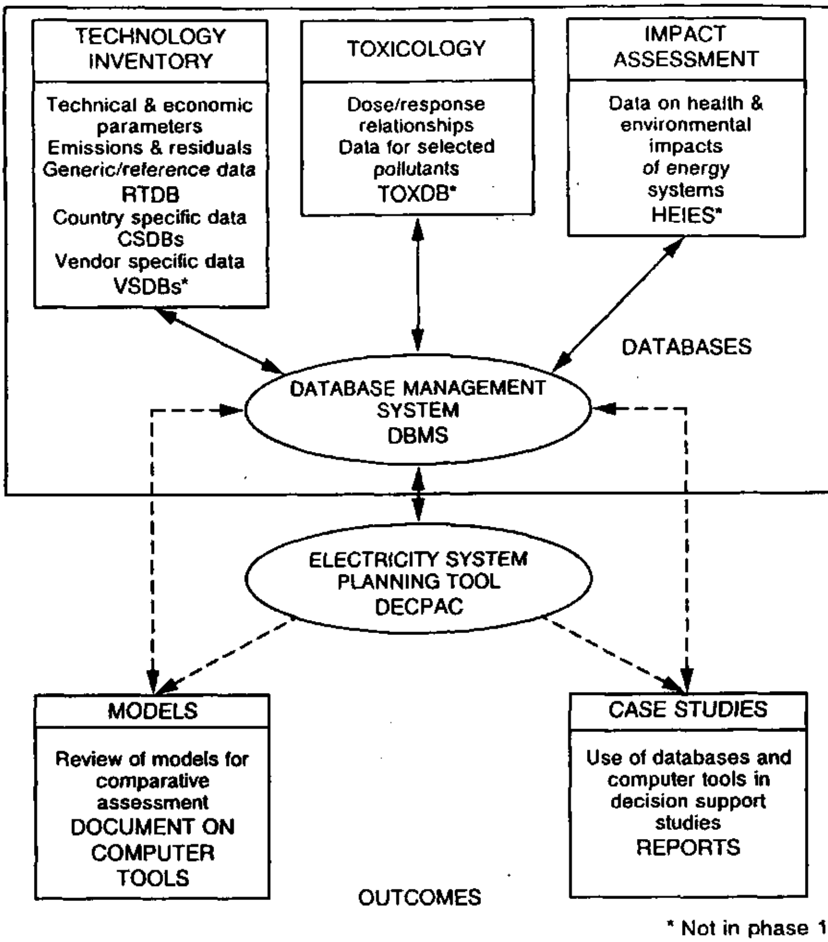

FIG. 2. Schematic structure of the DECADES project [1].

The first phase of the project focused on four main tasks: establishment of technology inventory databases and an information system; development of an integrated software package for comparative assessment of energy chains and electricity system expansion strategies; review of methodological approaches to comparative assessment; and carrying out of case studies illustrating the use of data and tools in decision support studies for the electricity sector. This paper presents preliminary results obtained for the first two tasks.

The schematic structure of the project is shown in Fig. 2. An outline and a general overview of the DECADES project can be found in Ref. [1].

In order to meet the objective of DECADES, it is necessary to have a comprehensive and consistent set of information and analytical models that support comparative assessment. Such a set of data is broad and complex and includes a number of data that are already compiled and stored in existing databases. Therefore, it was decided to adopt a modular approach and to group the information in three main databases addressing respectively the issues of: technology inventory, dose/response relationships for pollutants, and health and environmental impacts assessment.

In phase I of the DECADES project, the main effort has focused on establishing credible, reliable and up-to-date technology inventory databases covering all steps in energy chains for electricity generation by fossil fuels, nuclear and renewable energy sources. The toxicology database (TOXDB) covers dose effect relationships for pollutants released by the different electricity generating chains. The database on health and environmental impacts of energy systems (HEIES) for electricity generation gives information derived from published studies on the assessment of impacts from different fuel chain facilities and electricity generation plants.

2. TECHNOLOGY INVENTORY DATABASES

The technology inventory databases provide generic as well as country specific and region specific information on technologies currently used or expected to be commercially available in the coming two to three decades. Two types of technology inventory databases were established: the reference technology database (RTDB) and the country specific database (CSDB).

The RTDB contains generic data on technical, economic and emission parameters of energy chains using fossil, nuclear and renewable energy for electricity generation. The structure of the RTDB is described in detail in Ref. [2].

The technologies stored in the RTDB cover all the steps in the energy chain, from fuel extraction to waste disposal. Figure 3 is a schematic representation of a typical fuel chain. Each step of the energy chain is decomposed into construction, operation and dismantling processes. The steps can be divided into three groups:

(a) The front end of the chain, which extends from the extraction or harvesting of fuel to the delivery of processed fuel to the power plant site;
(b) The conversion step, where the energy contained in the fuel is transformed to electricity;
(c) The back end, which starts with transportation of waste, spent fuel and by-products and ends with disposal of waste.

In the energy chain, several streams could be defined for: fuel, waste, by-products, auxiliary materials (limestone, ignition fuel, etc.), energy (electricity, fuels, heat) used in processing facilities, and raw materials used in construction and

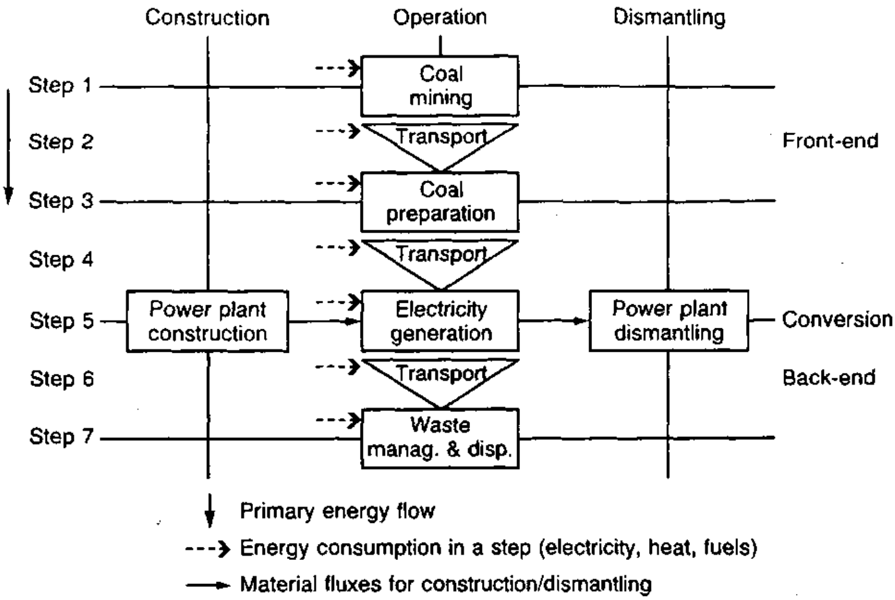

FIG. 3. Schematic representation of a coal fuel chain [3].

dismantling of the chain's facilities (the cement used for constructing the dam of a hydropower plant, the glass used for constructing solar collectors, etc.).

Similar schematic diagrams, highlighting the boundaries of the chains, have been established for the different fossil fuel, nuclear and renewable (hydro, biomass, solar, wind, geothermal and waste incineration) energy chains. The pollution abatement devices of power plants are artificially considered as a separate step in the chain. This approach has been adopted in order to reduce the number of facilities to be stored in the database. Variation of the same power plant could be obtained by combining the facility with different pollution abatement devices (SO_x, NO_x and particulates).

Furthermore, to obtain a higher level of generalization and to facilitate data collection, these different energy chains are merged into a general chain, which is shown in Fig. 4. Annotations are given for the different levels in the general chain diagram. The levels indicated in this schematic diagram are described further in the paper.

In the RTDB, a three-level scheme is used to define a process: technology, technology type and facility. For example, coal steam boiler is a technology used in the electricity generation step — *Level VI* — in a coal energy chain; and uranium mining — underground is a mining technology — *Level II* — in a nuclear energy chain. For a given technology there may be several variations, called technology

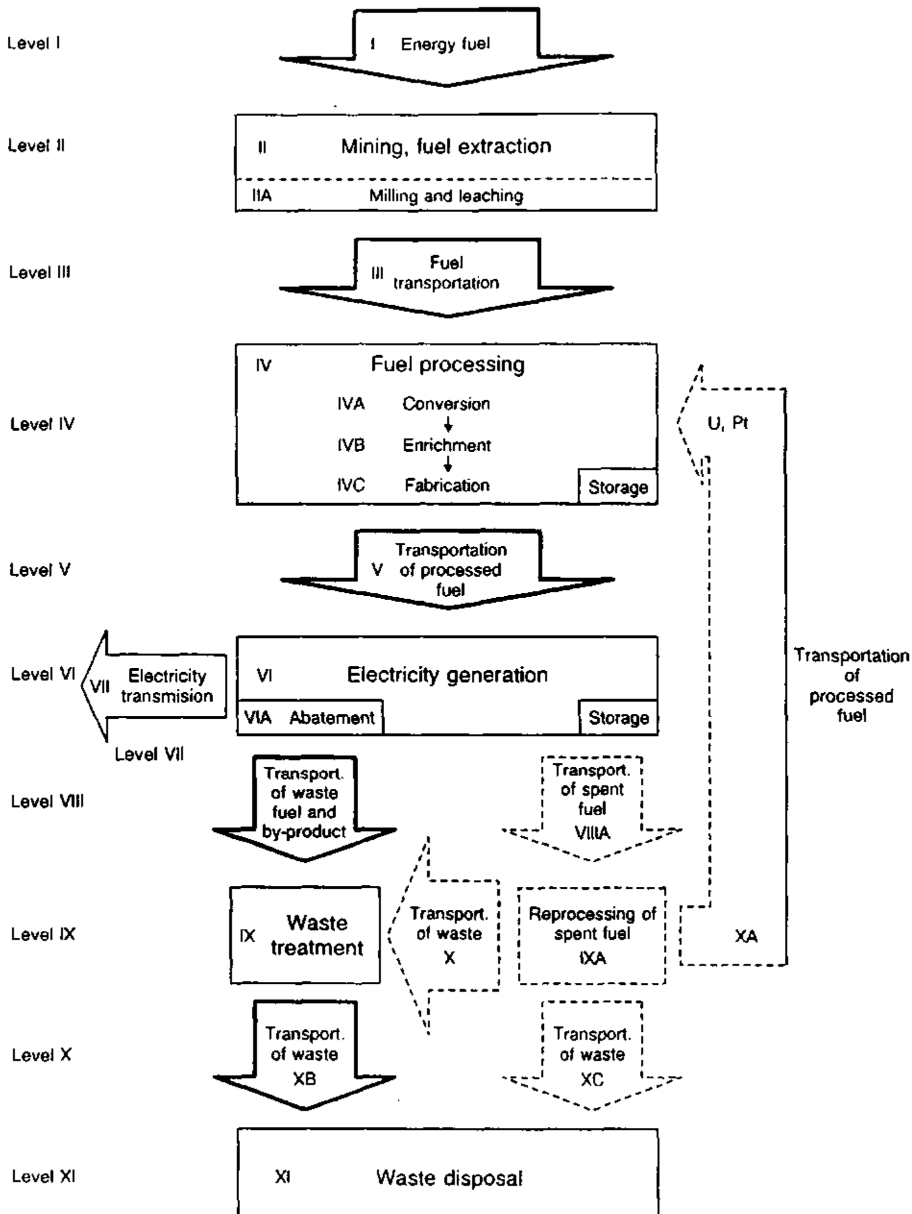

FIG. 4. Graphical representation of a generalized fuel chain [3].
Dotted lines indicate the back end of a nuclear chain with a closed fuel cycle.

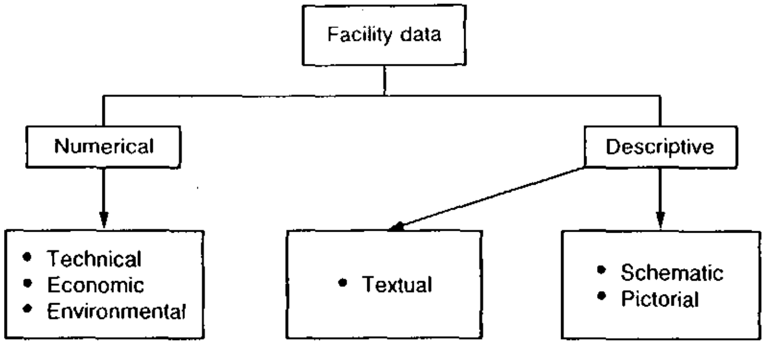

FIG. 5. Characterization of a facility in the RTDB and CSDBs.

types, and for a technology type several specific facilities may be introduced. A facility refers to a single unit in a multiple unit plant. Several units of the same type, or a combination of an electricity generation facility with one or several pollutant abatement devices, are referred to in the RTDB as a plant.

To meet the objective of providing comprehensive information on energy technologies, a facility is described in the database by descriptive textual, schematic or pictorial information (see Fig. 5) as well as numerical data.

The *numerical data* are divided into three main groups: technical data, economic data and environmental data (emissions, residues and other burdens). Each numerical parameter can have minimum, average and maximum values. The average value of a parameter, which is not necessarily the arithmetic mean between the minimum and maximum values, is used in calculations. A numerical entry has an attached comments field, to be used in describing the assumptions made, the values in the original unit of measure, currency exchange rates, categories included in the numerical value, or a qualitative ranking of the information.

A general reference to the source of the data set for a facility can be given, as well as specific references for individual data items when these are different from the general reference. The references are organized by titles and authors and there is a single consolidate list of references for all of the DECADES databases.

One of the major difficulties that had to be overcome in implementing the numerical part of the technology inventory databases was related to the necessity to store information for a wide variety of different facilities. Gas turbine or pulverized coal facilities are described by characteristics such as net output capacity, heat rate and scheduled maintenance. Transportation or waste disposal facilities are described by completely different characteristics. The solution adopted was to store in the database, together with the numerical values, the list of technical, economic and environmental characteristics (the characteristic name, unit of measure, etc.) needed to

TABLE I. SUMMARY OF THE TECHNOLOGIES COVERED BY RTDB/CSDBs — LEVEL VI — ELECTRICITY GENERATION STEP

Fossil fuels	Nuclear	Renewable energies
Coal steam boiler (CSB)	*Light water reactor (LWR)*	*Hydropower (HYD)*
Pulverized coal (PC)	Conventional pressurized	Run of river (HYDR)
Cyclone furnace (CF)	water reactor (PWR)	Storage (HYDS)
Spreader stoker (SS)	Advanced pressurized water	Pumped storage (HYDP)
(CO_2 recovery,	reactor (APWR)	(small, large)
O_2/CO_2 burning)	Conventional boiling water	
	reactor (BWR)	*Combustion biomass systems*
Atmospheric fluidized bed	Advanced boiling water	*(incl. industrial and*
combustion (AFBC)	reactor (ABWR)	*municipal waste)*
Circulating (CFBC)		Wood steam boilers (WSB)
Bubbling (BFBC)	*Pressurized heavy water*	Circulating FBC
	reactor (PWR)	Integrated gas,
Pressurized fluidized bed		combined cycle
combustion (PFBC)	*Gas cooled reactor (GCR)*	
Combined cycle	Conventional (GCR)	*Solar thermal (ST)*
Circulating (CPFBC)	High temperature (HTGC)	Solar tower (ST)
Bubbling (BPFBC)		Parabolic trough (PT)
	Liquid metal reactor (LMR)	Parabolic dish/Sterling (PB)
Coal gasification (CG)		
Non-integrated (GCC)	*Fast breeder reactor (FBR)*	*Solar photovoltaic (PV)*
Integrated (IGCC)		Photovoltaic crystalline
Integrated gasification		(PVCr)
(HAT)		Photovoltaic amorphous
		(PVAm)
Coal fired combustion		Photovoltaic thin film
turbine		(PVTf)
(see gas fired		Photovoltaic concentrators
combustion turbine)		(PVCt)
Improved cycle (IC)		*Wind (WIN)*
Gasification/PFBC hybrid		Horizontal axis (HAWT)
Binary Rankine cycle		Vertical axis (VAWT)
Magnetohydrodynamic		(onshore, offshore)
Gas steam boiler (GSB)		
Conventional (GSB)		

TABLE I (cont.)

Fossil fuels	Nuclear	Renewable energies
Gas fired combustion turbine (GT)		*Geothermal (GEO)*
Simple cycle heavy duty (GTSCh)		Conventional
Simple cycle aeroderivate (GTSCa)		Binary
Steam injected gas turbine (STIG)		Geopressurized
Humid air turbine (HAT)		Back-pressure
Combined cycle (GTCC)		Direct steam
		Flashed steam
		Wave
		Tidal
Fuel cell (FC)		
Phosphoric acid (PAFC)		*OTEC*
Molten carbonate (MCFC)		
Solid oxide (SOFC)		
Oil steam boiler (OSB)		
Conventional (OSB)		
Diesel engine (DE)		
Conventional (DE)		
Oil fired combustion turbine (CT)		
(see gas fired combustion turbine)		

describe a particular facility. This technique allowed a very flexible database model to be constructed; this is described in detail in Ref. [4]. Furthermore, the characteristics were divided into groups, such as airborne emissions, water effluents and solid waste, and into sub-groups, such as greenhouse gases and radionuclides. At present, the facilities stored in the RTDB are described by more than 440 characteristics.

Table I presents the technologies and technology types covered in the RTDB for power plants. The full list of power plants as well as the technology types and facilities for the front end and back end of the energy chains are described in detail in Ref. [2].

TABLE II. CODIFICATION OF THE DEVELOPMENT STATUS OF FACILITIES

M	Mature	Significant commercial experience available (several operating commercial units)
C	Commercial	Nascent commercial experience
D	Demonstration	Concept verified by industrial scale demonstration unit
P	Pilot	Concept verified by small pilot facility
L	Laboratory	Concept verified by laboratory studies and initial hardware development
I	Idea	No system hardware development
O	Obsolete	Not available for new projects

The facilities included in the RTDB were selected following the recommendations of experts in the different energy chains. The basic criterion used for selecting a given facility is that it should be representative, i.e. either widely used at present or expected to be available for large scale use in the next decades. Therefore, the RTDB provides the users with generic information which might be taken in default of country specific information. In this respect, the RTDB provides rather general design data evaluated by experts in the different energy chains. Owing to the nature of the information provided in the RTDB, the database will require maintenance and updating on a regular basis in order to keep pace with technological developments.

For some steps in the energy chain, e.g. mining, it was difficult to define a reference or generic facility. To overcome this problem, two types of mines were stored in different categories: model mines having the average performances for several mines; and representative mines providing data for specific, typical mines.

The RTDB stores data for mature technologies as well as for demonstration or pilot technologies. The status of development of a technology is indicated in the database by a one-letter code, as listed in Table II. For future technologies an estimated year for market availability could be introduced.

Data on fuel characteristics are also included in the RTDB. A four-level scheme is used to define a fuel: fuel group (fossil fuel, nuclear, renewable), fuel source (solid fuel, liquid fuel, gaseous fuel, etc.), fuel type (lignite, sub-bituminous, bituminous, peat, etc.) and fuel sub-type (Illinois #6, Kuznesky, Dayton, etc.). Groups of characteristics, such as proximate analysis, ultimate analysis and mineral ash composition, were defined. The fuels database contains data on primary energy sources (e.g. crude oil) as well as processed fuels (diesel, heavy fuel oil, etc.). Information on the emission factors for producing processed fuels is also included.

The information provided for a facility is largely dependent on the fuel used. If the fuel is changed, then the technical, economic and environmental characteristics of the facility will change. Therefore, for the facilities stored in the RTDB the fuel is indicated and the fuel characteristics are stored in the energy sources database. If a facility can use several fuels, it is recommended to store separate facilities in the database for each fuel used.

In addition to the fuel groups described above, a special category (others) is defined to store energy characteristics (electricity, heat, mechanical) in the database. For example, several types of fuel mixes for generating the electricity consumed by fuel chain facilities could be defined. The characteristics of electricity as an energy source are the emission factors (CO_2, SO_x, NO_x, etc.) and the price. Similar data are added also for fuels used in transportation, mining, etc.

Descriptive information can be included for technologies, sub-technologies and facilities, as well as for fuels, for energy chains as a whole or for steps in the chain. Although this information is not essential, it does help in clarifying the basis for the numerical data.

Textual information can be divided into topics, such as general characteristics of the facility, cost and emission issues, possible technological improvements and implementation issues; a navigator is provided which permits direct access to a topic.

Pictorial information is stored in an open format and can be directly accessed from the numerical database or from the textual descriptions. At present, over 110 simplified mass flow diagrams, block diagrams, physical principle diagrams or pictures presenting facility details are stored in the database. Special techniques were used to minimize the storage space required by such information.

The collection and consistency checking of data for the RTDB was started in 1993. Data collection forms, covering eleven energy chains, were designed and distributed to different international organizations, institutes and organizations from IAEA Members States, and to individual experts. Special efforts on data collection and consistency checking were carried out also by the European Commission, the Nuclear Energy Agency of the OECD (OECD/NEA), the International Bank for Reconstruction and Development (World Bank, IBRD), the Organization of Petroleum Exporting Countries (OPEC), etc. As a result of these activities, data for the major energy chains, containing 270 typical facilities and 90 energy sources, were collected. The database, together with the data management system, was distributed to a large number of selected users for testing and evaluation. Feedback from users is providing guidance on enhancing the capabilities in order to better meet the requirements of analysts and decision makers.

The CSDBs are the second type of technology inventory database developed within the DECADES project framework. These databases address the need to store specific information on a country's existing electricity generating chains and electricity systems as well as on candidate technologies for electric system expansion. The CSDBs, following the structure of the RTDB and supplemented with data specific to the electricity system, were constructed by more than 15 countries, with technical support from the IAEA.

The 15 CSDBs contain: 1300 facilities, 500 energy sources and 900 energy chains, with over 20 000 numerical entries. Basic technical, economic and environmental parameters are included in the databases for all facilities. However, additional numerical data, descriptive information and references to the sources of information should be added. In most of the CSDBs, the main data gaps are for facilities in the front end and back end of the energy chains.

A large number of the facilities included in the CSDBs pertain to existing units. Not surprisingly, significant differences could be noted between the technical performance, cost data and emission factors for similar technologies in different countries. At present, the CSDBs include both real facilities and typical facilities derived by averaging the performance of several similar units. Both types of facilities might be used for carrying out comparative assessments of energy chains or expansion studies of electricity systems within the DECADES project or for other applications.

A large variety of typical coal, gas and oil fuels are included in the CSDBs, as well as detailed information, such as mineral ash composition and radionuclides contained in coal. In some countries, power plants use combinations of fuels (coal and oil), and it was necessary to include data on such special fuels.

The RTDB/CSDBs technology inventories provide a comprehensive set of data and information for use in comparative assessment of plant characteristics, full energy chain characteristics and electricity system expansion strategies. The results obtained so far, the feedback provided by users, and the great interest manifested by institutes, organizations and universities in Member States are more than encouraging and demonstrate the usefulness of these databases.

3. ANALYTICAL FRAMEWORK OF DECADES

Databases alone, however, are not sufficient for carrying out comprehensive comparative assessment of electricity generation chains and strategies. Such studies require analytical tools providing capabilities for analysing energy chains and electricity generation systems, and for assessing impacts. The levels of comparative assessment addressed in the DECADES project framework are presented in Fig. 6.

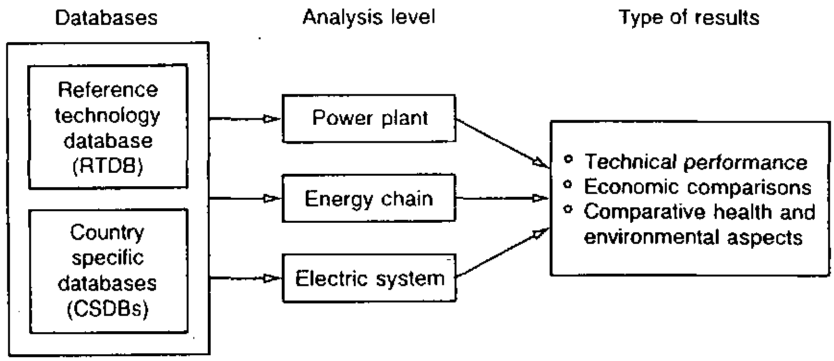

FIG. 6. Levels of analysis in the DECADES project.

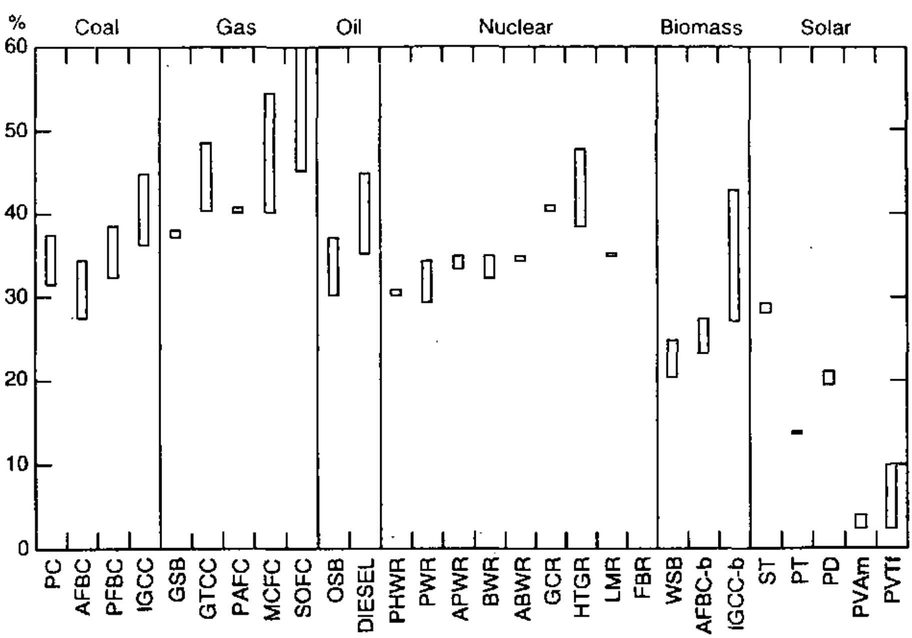

FIG. 7. Preliminary comparison of generating efficiency for RTDB technologies (see Table I).

3.1. Power plant comparisons

Several types of comparison at the power plant level can be carried out by using the data stored in the RTDB/CSDBs. Reporting capabilities were developed to permit side by side display of the data for different facilities in order to allow direct comparisons to be made. This section presents preliminary comparisons of generating efficiency, air emissions and costs for the different technologies included in the RTDB/CSDBs.

Figure 7 shows the range of net efficiency values for several technologies included in the RTDB. The performance of new technologies, with different combustion processes and advanced power cycles, can exceed the best performance of conventional technologies. Significant improvements in the generating efficiency are noted for technologies based on gas, while the expected efficiency improvements for the other technologies appear to be only marginal.

The generating efficiency data are strongly influenced by the characteristics of the fuel used, the maintenance of the power plant and other local conditions. Plant efficiencies vary from country to country (see Fig. 8), and in many countries they are lower than the values presented in Fig. 7 for coal, oil and gas technologies.

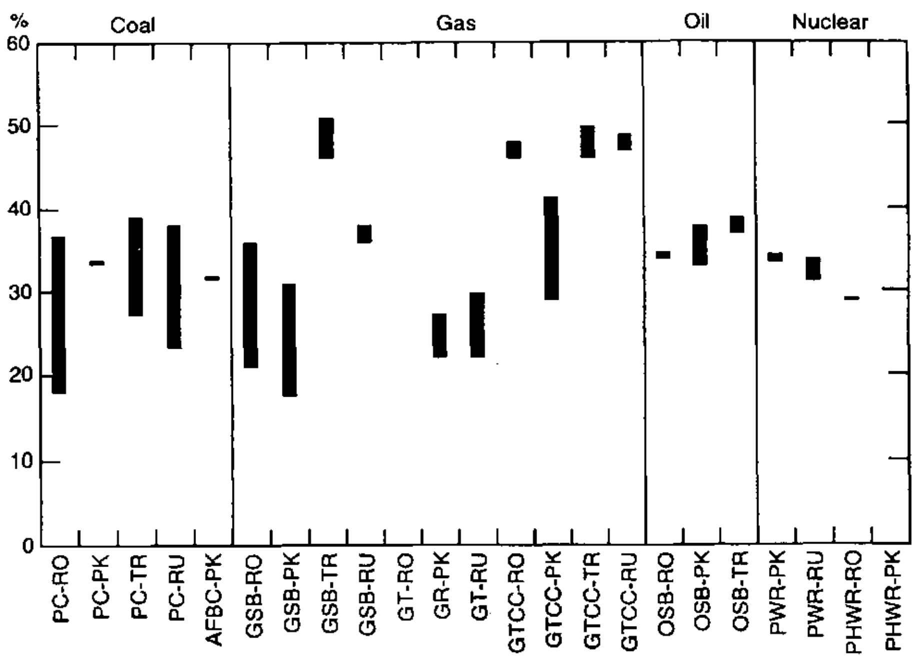

FIG. 8. Preliminary comparison of generating efficiency for CSDB technologies (RO — Romania, PK — Pakistan, TR — Turkey, RU — Russia).

Figures 9, 10 and 11 illustrate the CO_2, NO_x and SO_x emission factors for the following types of power plants: pulverized coal with flue-gas desulphurization (PC+FGD), pressurized fluidized bed combustion (PFBC), integrated gasification combined cycle (IGCC), gas turbine combined cycle (GTCC) and oil fired steam boiler (OSB). The plants have the same size (500 MW) and the coal fired plants use similar fuels.

The highest CO_2 emissions (Fig. 9) result from the coal fired options. These technologies show a considerable range of CO_2 emissions as a result of significant variations in efficiency of power generation. The GTCC has the lowest emissions. The emissions from oil fired units are within the spread of the results for natural gas and coal, and depend upon the quality of the heavy oil used. The CO_2 emissions from the GTCC plant are less than half of those for coal options.

Figure 10 summarizes the emissions of nitrogen oxides. The results should be compared with caution, since different levels of NO_x mitigation are applied: the PC+FGD and OSB plants use low-NO_x burners; the IGCC facility uses injection of nitrogen, from the air separation unit into the gas turbine, to limit NO_x formation; and the GTCC plant uses advanced burner technology. The NO_x emissions from the PC+FGD facility could be further reduced using additional NO_x control devices (selective catalytic reduction, SCR).

The remarks on the pollution control devices for NO_x apply also for SO_x emissions, as presented in Fig. 11. The highest SO_x emissions are for PC technologies.

The emission factors presented indicate a strong dependence on the fuel used, the generating efficiency, the pollution control measures included in different designs, and other factors. Furthermore, it is generally agreed that consideration of the environmental impacts only at the power plant level is not sufficient. Although in some cases, such as CO_2 emissions, the power plant is the major contributor in the energy chain, for other emissions and burdens other steps in the chain are more important.

Figure 12 shows the total capital requirements for PC plants, OSB plants, GTCC plants and nuclear plants in several countries.

Special efforts were made to develop and implement calculation algorithms to support a modular approach to air pollution abatement technologies. This allows analysis of the influence that the implementation of such devices would have on the emissions and costs of the power plant. Calculation algorithms were developed by the Argonne National Laboratory for seven abatement technologies: electrostatic precipitators, fabric filters, wet FGD, dry FGD, furnace sorbent injection, hot SCR and cold SCR. Using these algorithms, a power plant module containing up to three abatement technologies can be simulated. The module is constructed using the data stored in the RTDB/CSDBs and estimations are made for: capital and overnight costs, fixed and variable operation and maintenance (O&M) costs, reagent consumption, if any, internal electricity consumption, and the impact on efficiency of adding

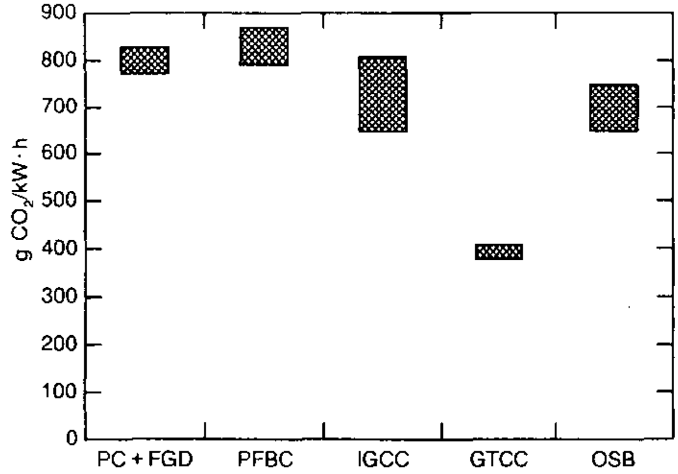

FIG. 9. Emissions of CO_2 — power plant level.

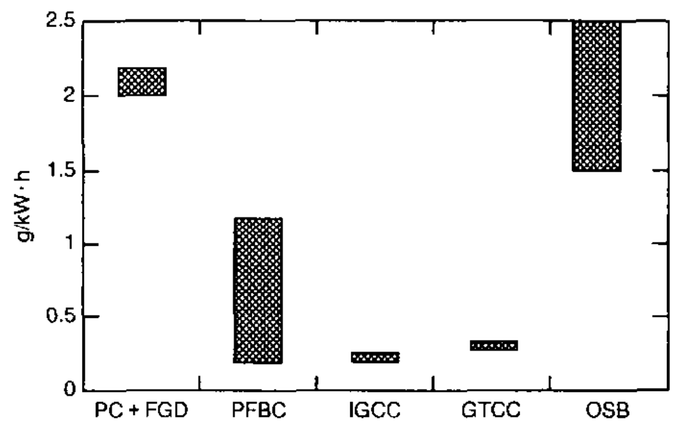

FIG. 10. Emissions of NO_x — power plant level.

abatement devices to the power plant. Furthermore, the effects on emissions and costs can be estimated at the level of either the individual energy chains or the complete electricity system.

3.2. Energy chain analysis

The DECADES project approach covers the full energy chains for electricity generation. However, in contrast to life cycle analysis (LCA), the secondary and

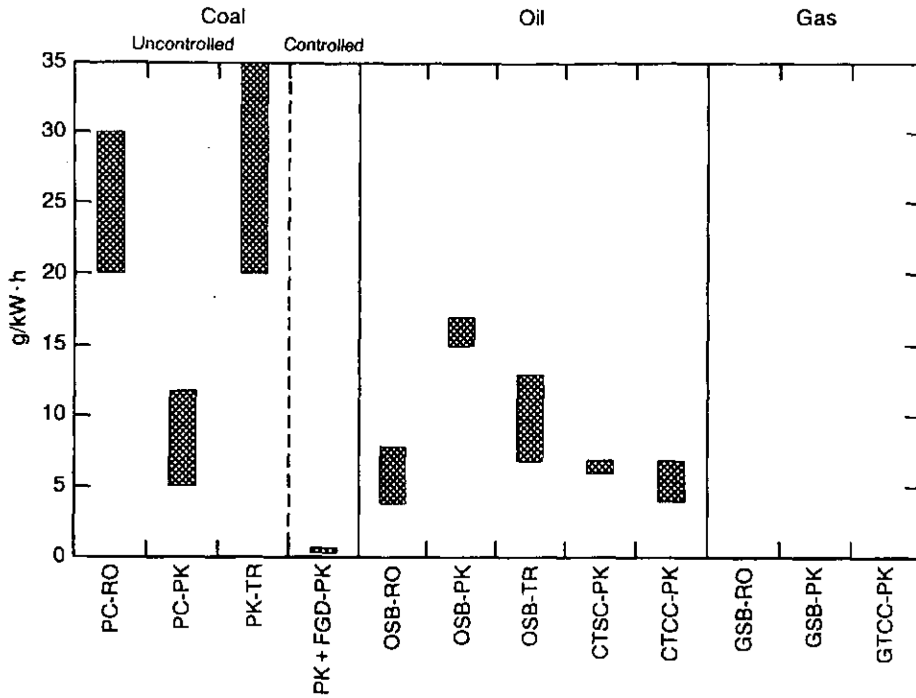

FIG. 11. Emissions of SO_x — power plant level. (RO — Romania, PK — Pakistan, TR — Turkey).

other levels, e.g. the production of materials used for manufacturing components of an energy chain facility itself, are excluded at present.

A modular approach to the energy chain representation was adopted. Each step in the chain is considered as a separate module, having specific data stored in the energy chain database. In order to define a step, a specific facility is selected from the RTDB or CSDBs. Additional data, such as distance for transportation steps, lead time (with respect to the electricity generation step) for the fuel processing steps, specific design factors for the facility selected, and types of auxiliary energy inputs, are stored as step definition data. A fuel for the chain should also be selected from the energy sources database. Textual descriptions can be introduced and stored at each step or for the whole chain. The chains are grouped in the database by the predominant energy source used for electricity generation.

Figure 13 is a modular representation of the coal chain. The upper part of the diagram contains the energy source — *Level I*, which in this case is bituminous coal, medium volatile. The rest of the diagram contains the chain steps. The facility selected is shown near each step. In this case, the electricity generation facility is

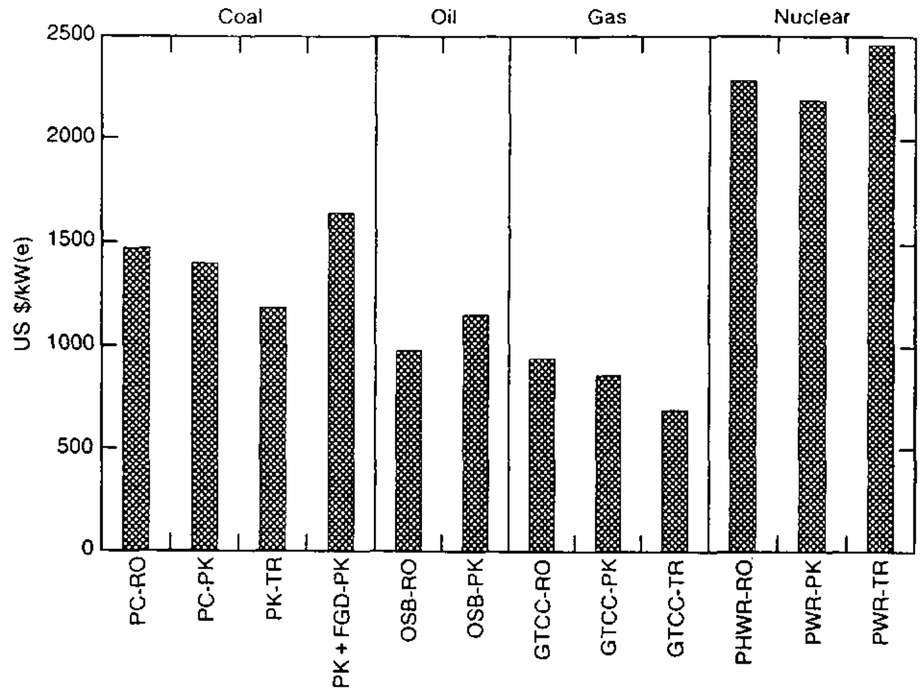

FIG. 12. Investment costs — power plant level.
(RO — Romania, PK — Pakistan, TR — Turkey).

a coal steam boiler using pulverized coal, and the unit size is 500 MW. The specific mass flows (g/kW·h) as well as the transportation distances are indicated on the diagram.

In order to simplify the construction of new chains, a reference or base chain has been defined in the RTDB for every type of energy source. A new chain, called 'user type', is obtained by cloning and modifying the reference chain. Modifications could include: different facilities for some steps, different fuel, different transportation distances, etc. The steps that should not be considered in a particular case, such as mining for imported coal, could be deleted. Using the modular description of the chain and the procedure described above, a large number of different chains can be defined very easily.

However, this flexibility in defining new chains calls for algorithms to verify the feasibility of the combinations selected. Several types of checking are performed, based on lists of feasible combinations stored in the database:

— Fuel: technology restrictions (the selected fuel cannot use the selected mining technology);

— Fuel switching (facility data stored in the databases were given for a different fuel);
— Power plant: abatement technology restrictions (the selected power plant cannot use the selected abatement technology, or it cannot use it in combination with a previously selected other abatement technology).

Simple algorithms have been developed to compute mass flows of fuels and waste during the economic lifetime of the power plant and to calculate the levelized electricity generation cost. In a first pass, the calculations are carried out from mining (*Level II*) to electricity generation (*Level VI*), and modifications in characteristics of the primary energy source are taken into account. In a coal chain, for example, the preparation step (*Level IV*) improves the heat value of the coal and reduces the ash and sulphur contents. In a second pass, the calculation starts at electricity generation (*Level VI*) and is carried out backwards to mining (*Level II*) and forward to waste disposal (*Level XI*). It is assumed that the energy chain is in equilibrium, i.e. the mass flows of fuel, by-products and wastes per kW·h(e) generated are constant for a given technology configuration. However, fuel inventories as well as lead and lag times in the energy chain are accounted for in the cost calculation. One-time impacts, such as the initial fuel loading and the waste disposal from decommissioning, are distributed over the electricity generated during the

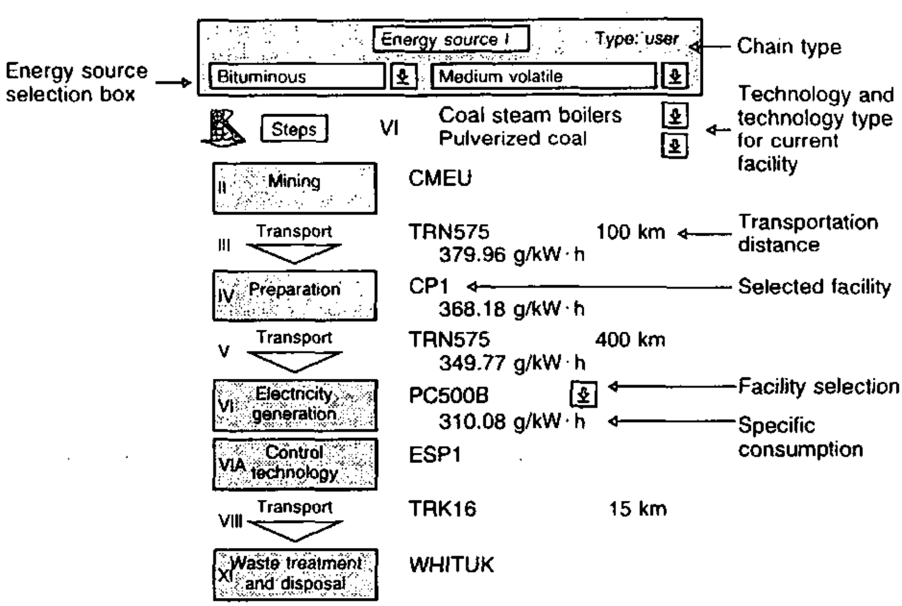

FIG. 13. Modular representation of the coal chain.

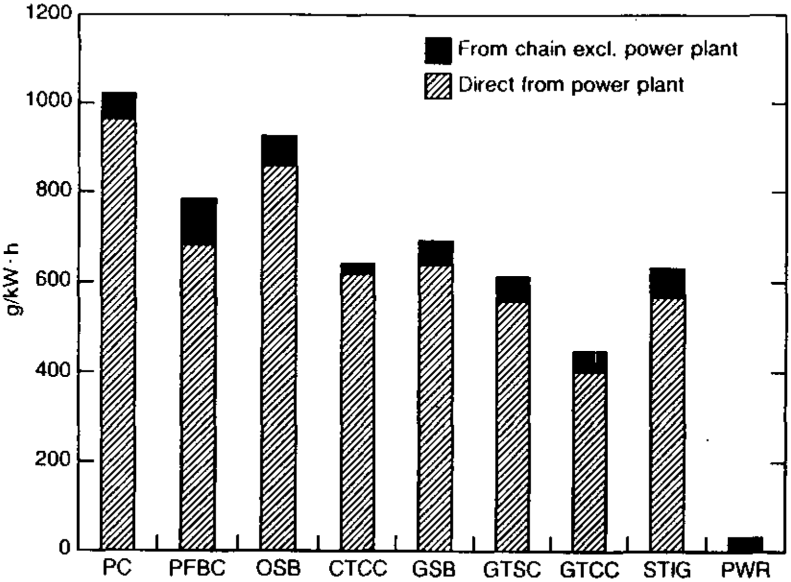

FIG. 14. Emissions of CO_2 — full chain.

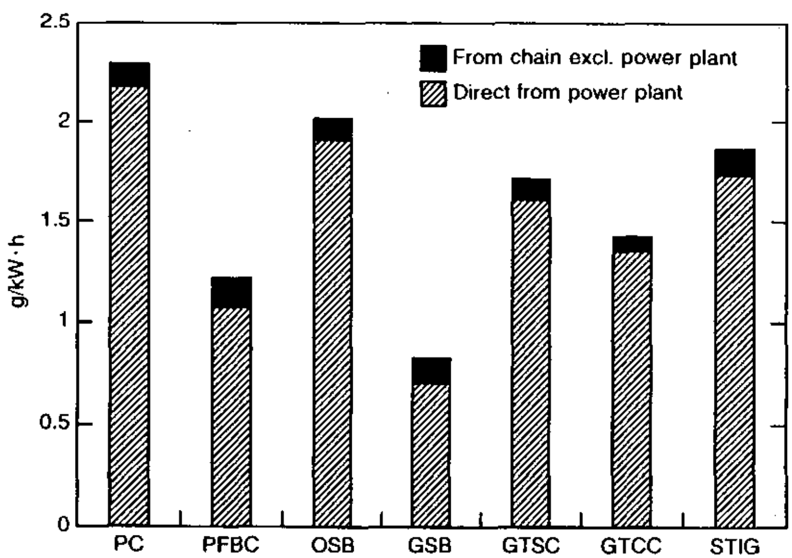

FIG. 15. Emissions of NO_x — full chain.

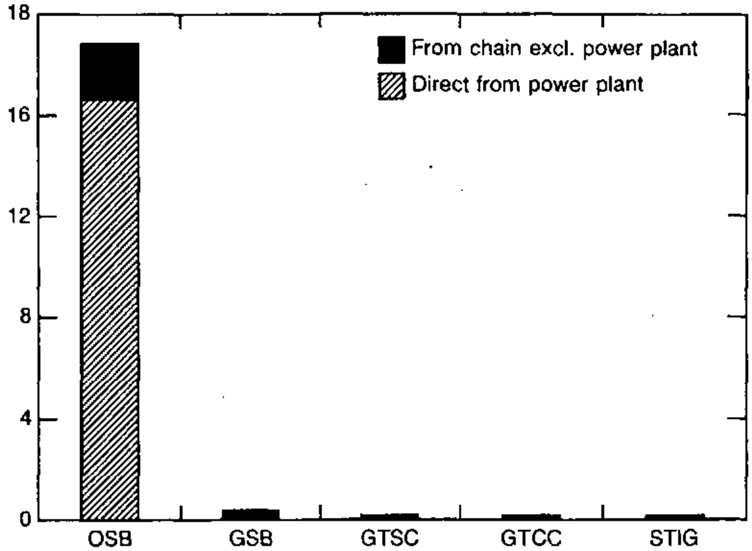

FIG. 16. Emissions of SO_x — full chain.

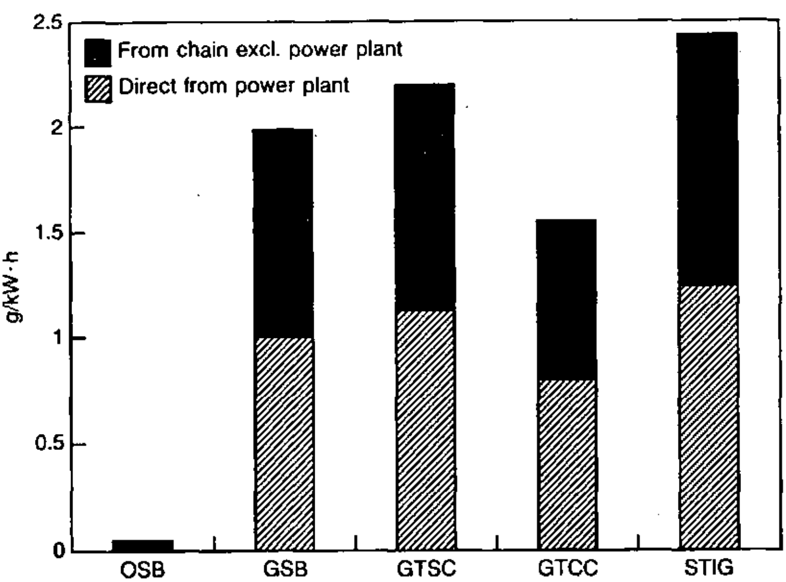

FIG. 17. Emissions of CH_4 — full chain.

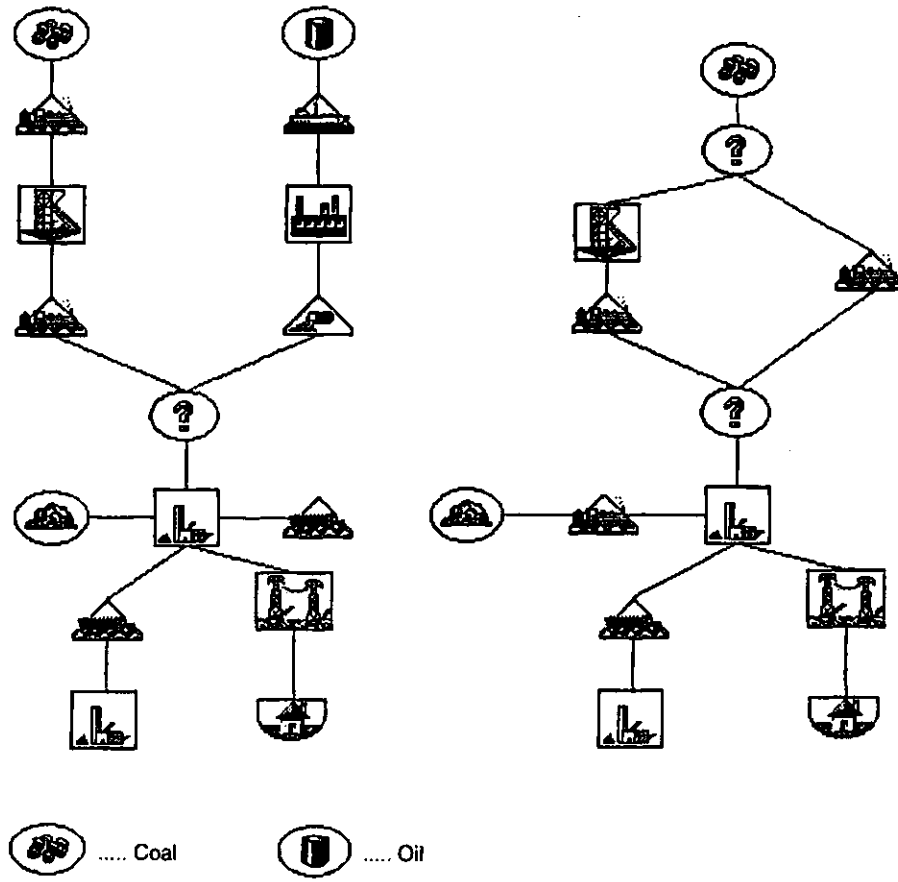

FIG. 18. Extended chain representation.

economic life of the plant. For multi-output steps, such as oil refining, allocation criteria are used.

The methodology presented offers great flexibility in considering different options of energy chains and can be used to determine emissions and costs. In contrast to other methodologies which use only one chain defined by average values for a country, such as average distance for lignite transportation, the DECADES approach allows the user to model real life situations. However, one can construct and assess several typical chains and then average the emissions and costs obtained. Moreover, the sensitivity to modifications of different factors could be studied in the energy chain approach.

Direct comparisons of different energy chains are possible by using a side by side display, combined with simple access to emissions, residuals and economic data. Figures 14–17 illustrate results obtained for CO_2, NO_x, SO_x and CH_4 emissions for a typical liquid fuel chain, several gaseous fuel chains (gas steam boiler, gas turbine simple cycle, gas turbine combined cycle, steam injected gas turbine), and nuclear and biomass chains. The contribution of the power plant and of the rest of the chain are presented separately.

Regarding power plant level comparisons, the preliminary results obtained using CSDB chains differ from country to country. Although many chains are based on domestic fuels, a significant number are based on imported fuels and the mining steps therefore are missing. The situation is similar for the nuclear chains because the fuel is imported in the majority of the countries that established CSDBs. In some cases, composite transportation steps had to be included, for example combining sea transportation and land transportation. Some countries also have power plants that use a mix of fuels (e.g. coal and oil) or that switch from one fuel to another (e.g. from oil to gas) in different periods of the year. The database and the analytical model are flexible enough to permit such fuel mixes to be simulated.

The methodology presented, combined with the supporting databases, permits an efficient assessment of the energy chain emissions and the levelized energy cost. However, there are situations where the simplified energy chain representation is not enough. These situations are summarized as follows:

- Multiple fuel power plants or plants using a mixture of fuels (see Fig. 18);
- Multiple outputs from the power plants: electricity, heat (cogeneration), by-products, several types of waste;
- Same type of fuel coming from different mines or preparation facilities;
- Splitting of the fuel into several streams with different processing;
- Significant transportation or mining of auxiliary materials (limestone).

For these situations a prototype of an extended chain representation was developed (see Fig. 18). The data stored in the general chain representation can be used and further refined using the extended chain representation. This could be an enhancement, to be finalized in phase II of the DECADES project.

It should be noted that the annual emission calculations at the energy chain level are performed for an equivalent full power operation of the power plant without taking into consideration the interactions with other chains in a real electricity system. Significant differences may result when such interactions are taken into consideration.

3.3. Electricity system analysis

The primary goal of the electricity system analysis model (DECPAC) is to provide analysts and decision makers with an easy to use tool in support of assessments of different expansion strategies over a period of several decades. The DECPAC model was developed by the Argonne National Laboratory, drawing from aspects of

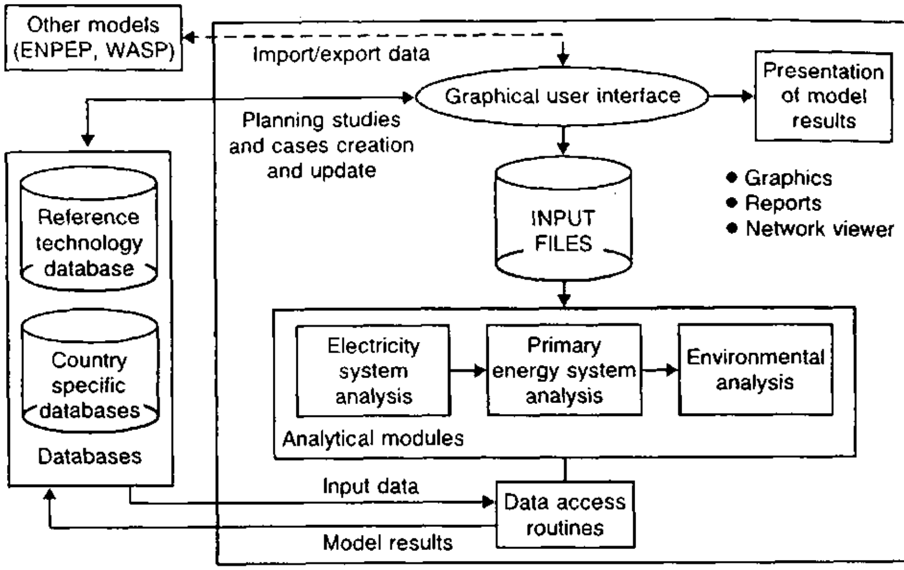

FIG. 19. System level analysis.

the IAEA's WASP and ENPEP packages, which address economic optimization. The main elements of DECPAC and the interlinkage with the databases are presented in Fig. 19. A detailed description of the model structure and capabilities is given in Ref. [5]. Some fundamental features are discussed below.

(a) The model is integrated with the RTDB/CSDBs. Information is exchanged through data access routines. A graphical user interface was designed to create input files for the model, to control the execution of the sub-modules and to present the results. Possibilities to import and export data in the format supported by the WASP and ENPEP models are also included. In this way, the user's previous investment in the IAEA planning tools is protected and the exchange of information between RTDB/CSDBs and other models is ensured.

(b) The electric system is represented by a mix of chains, as shown in Fig. 20. In the present representation, the back end of the energy chains is not considered. Planning studies are constructed using energy chains stored in the RTDB/CSDBs. Additional data, such as system load data, committed additions and retirements of power plants, economic data (discount rates, fuel escalation factors) and reliability data, are stored in CSDBs. Preliminary evaluations of candidate facilities can be performed through the use of screening curves (annual production costs versus capacity factor diagrams) before running the optimization model.

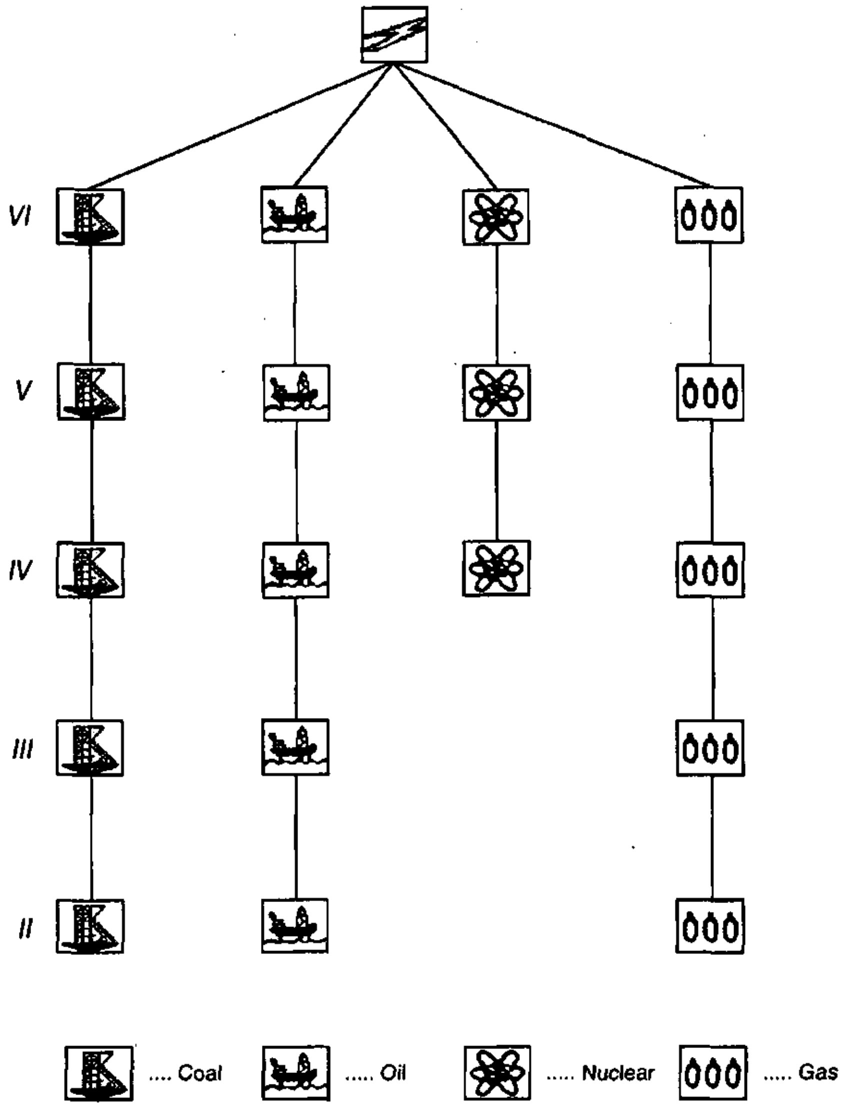

FIG. 20. Schematic representation of an electricity system by a mix of energy chains.

(c) A least cost expansion planning is performed, using simulation methods and dynamic programming to find the optimum strategy. This function is supported by the electric system analysis module (ELECSAM). The module can be used for screening purposes or to perform a full economic optimization. In the screening mode, a heuristic algorithm is used to generate annual configurations that span a wide range of possible expansion strategies, and dynamic programming is used to

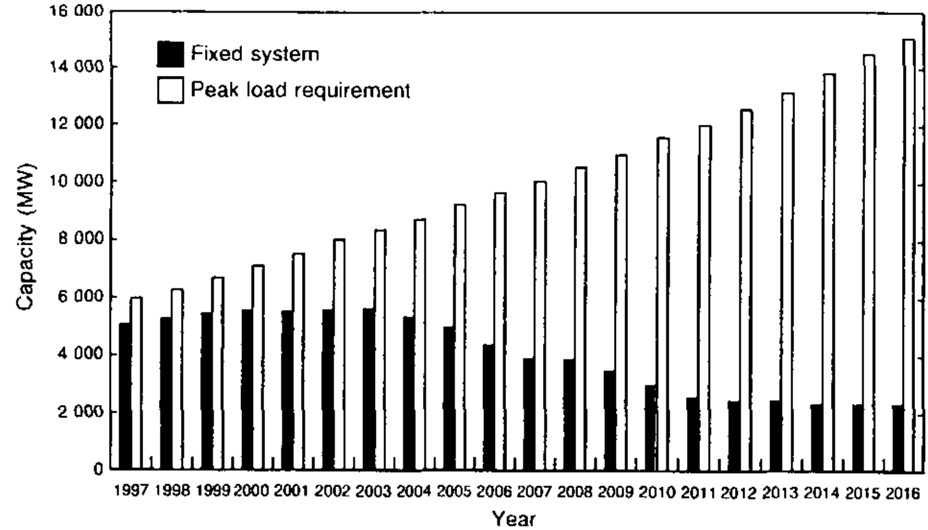

FIG. 21. Installed capacity in a fixed system and capacity required for peak load.

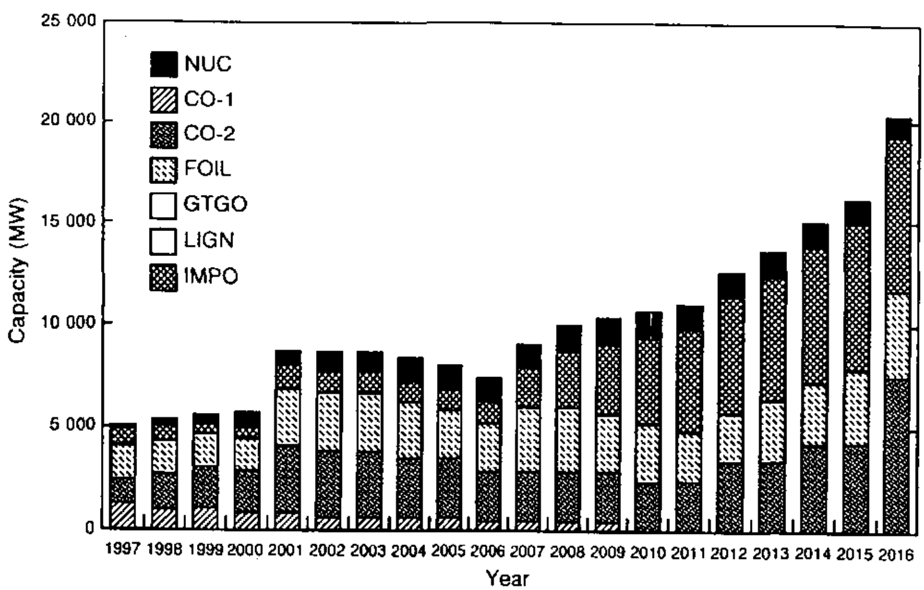

FIG. 22. Total installed capacity in a thermal system — screening mode.

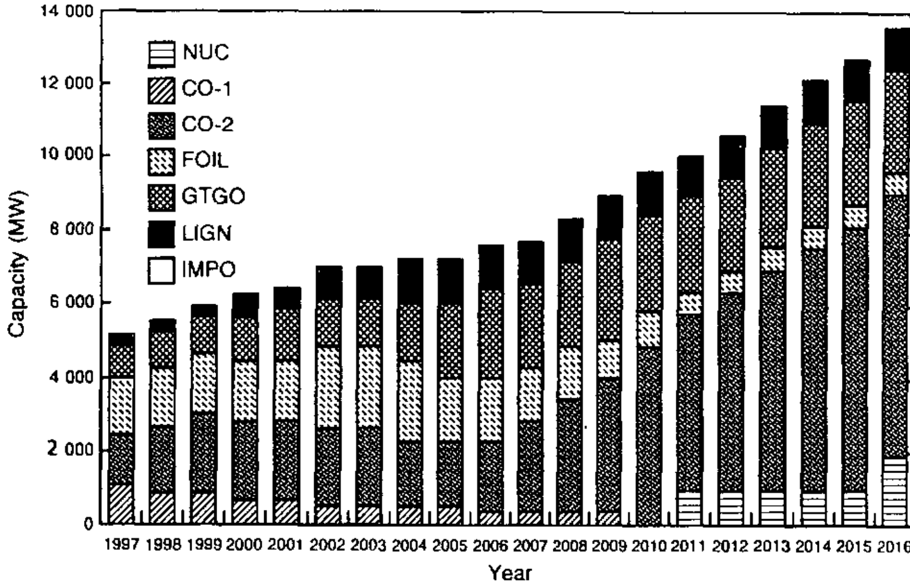

FIG. 23. Total installed capacity in a thermal system — optimization mode.

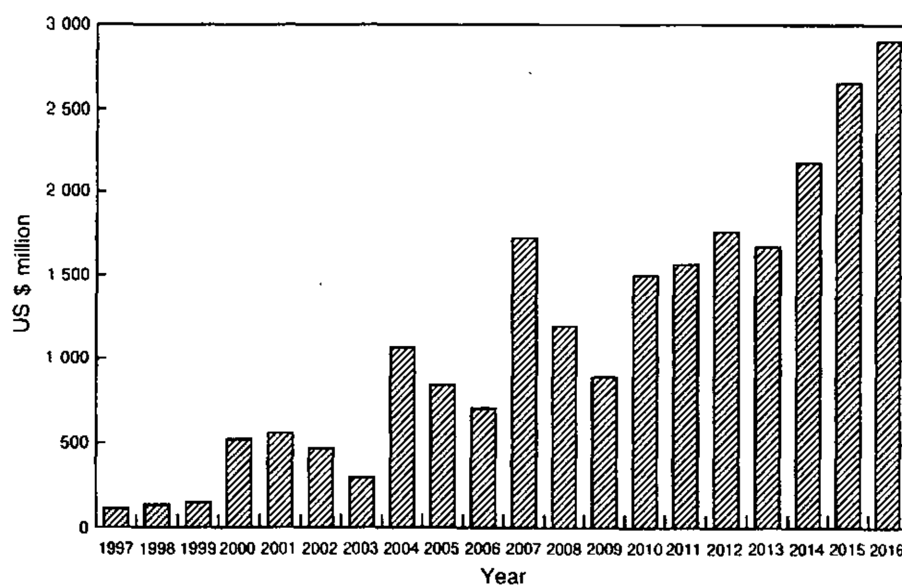

FIG. 24. Total system cost (constant 1997 price).

select a low-cost strategy. The optimization mode uses iterative passes to progressively improve the screening solution until the optimum expansion plan is found.

(d) The primary energy supply analysis module (PRENSAM) determines the fuel requirements based on the expansion plan provided by ELECSAM and calculates the mass flow of fuels through the front end steps of the chains.

(e) The environmental analysis module (ENVIRAM) calculates atmospheric emissions, waste generation and land use over the planning horizon. The effect of installing air pollution control devices on system expansion, total generation cost and emissions can be analysed in detail.

Some twelve scientific teams from different Member States are already testing the use of DECPAC for carrying out case studies. Preliminary results are reported in other papers presented at the Symposium.

Figure 21 illustrates, for a test case, the evolution over the study period of the capacity installed in the existing electricity system and the peak load requirements. The results of the system expansion plan obtained using a screening mode and an optimization mode are presented in Figs 22 and 23, respectively. For the screening mode, the approximation of the required peak load by new capacities added over the study period is rough. The optimum expansion plan, indicated by the optimization mode, smoothly follows the curve of capacity required for peak load.

The total system cost was also calculated (see Fig. 24), and a breakdown of the costs was provided for categories such as construction, operation, production and energy not served. Additional graphics for total electricity generation, capacity added, fuel consumption, environmental control device costs and control device cost effectiveness are provided in DECPAC.

Finally, air emissions, land requirements and solid waste were calculated, year by year and step by step, for every energy chain included in the system, and totals for the entire electricity system are given. As expected, the annual emissions of existing plants as well as of expansion candidate plants follow the capacity factor variations.

4. SOFTWARE DEVELOPMENT

The software requirements for the databases and the DECPAC model can be summarized as follows: user friendliness and graphical interface, to run on normal PCs using commercial database management systems, and a graphic oriented operating system. The targeted running time for the model is half an hour. To meet these requirements the software was developed to run under MS Windows.

The databases are implemented using an inexpensive, commercially available, relational database management system (Paradox for Windows). A very flexible data model was developed using specific database techniques (in database management terminology, level three of normalization). The data management system provides extended reporting capabilities (summaries, crostabs and full reports), support for ad hoc queries of the database (QBE or SQL) and open access to the data (ODBC).

Several types of users were defined and successive levels of complexity were attached to each type of user. Stand-alone and file server (ten simultaneous users) configurations were tested. A client server configuration for more users or for remote access to the databases is possible.

The computational and data access algorithms were reviewed several times in order to reduce the running time of the model. The feedback provided by the users was very helpful in enhancing the user friendliness of the software and in adding new features.

Special attention was given to the presentation of the results in the form of customizable graphics and reports. A network viewer was developed to display the emissions and energy flows for the energy system year by year.

Detailed user's guide documentation [3] was prepared and distributed for evaluation, together with the software, to scientific teams preparing case studies. A context sensitive help system and a glossary containing over 400 definitions are included in the software.

5. CONCLUDING REMARKS

The methodology presented addresses broad issues in the comparative assessment of energy chains and strategies, including the creation of comprehensive databases and integrated analytical models. The results obtained so far within the DECADES project demonstrate the effectiveness of the methodological framework developed. The computer tools have met with very great interest from Member States, in particular from developing countries and countries in transition; several countries are already using the databases and computer model presented in the paper.

However, it is necessary to have continuing maintenance, updating and improvement of the databases and the DECPAC software and to provide training in using the computer tools developed. Improvements in the capabilities to treat cogeneration plants, for modelling multiple fuel power plants (e.g. using oil and gas) and for modelling intermittent renewable energy systems are foreseen.

A very detailed quantification of emissions and other burdens is the cornerstone for comparative assessment studies, but this does not answer directly the question of which health and environmental impacts may result. The next phase of work could aim at developing estimates of such impacts and introducing additional decision support methodologies.

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INTEGRATION OF QUALITATIVE AND QUANTITATIVE INDICATORS IN COMPARATIVE RISK ASSESSMENT

M.J. CHADWICK
Stockholm Environment Institute

S.-O. RYDING
Federation of Swedish Industries

Stockholm, Sweden

Abstract

INTEGRATION OF QUALITATIVE AND QUANTITATIVE INDICATORS IN COMPARATIVE RISK ASSESSMENT.

The term *risk* is understood in rather different ways by the public and by scientists, and it has therefore proved difficult to evolve a framework for integrating qualitative and quantitative aspects of risk assessment. Considerable advance has been made in the analysis and quantification of health risks using epidemiology, test on organisms and modelling approaches to supply quantitative estimates. Comparative results have been presented as *mortality* or *morbidity* estimates, or some derivation of these, normalized for a 'unit of activity'. Approaches to the broad category of environmental risk assessment have progressed more slowly. Variation in the focus of interest on different organisms, or association of organisms, on different habitats, on physicochemical conditions or biological impacts, and a diversity of concerns about changes in structural or functional attributes, have all prevented a uniform approach that would enable integration and the formulation of comparative assessments. Some progress has been made through the use of a conceptual framework centred around the *pressure — state — impacts — response* approach. However, certain of these elements still require a method for integrating qualitative and quantitative aspects. A number of methods have been proposed; these include *ranked assessments, emission or ambient quality values* and *transgression of critical loads or critical levels.* There are also a number of management based approaches spanning relevancy to sector, industry, process, product and customer concerns. These approaches centre mainly around *life cycle assessment.* Future research has to focus not only on how integration might be achieved but also on how such integration will be able to facilitate comparative environmental risk assessments.

1. INTRODUCTION

Risk is a concept that is commonly accepted both by the public and in scientific and technical fields. The understanding of the concept, however, differs in relation to public and scientific interests, sometimes in rather obvious ways but often in a more subtle manner. In the scientific and technical arena, *risk* has a precise meaning: "the probability of an adverse event or condition". It is linked with the concept of *detriment:* "the probability of an adverse event multiplied by the extent of the damage caused". Thus, *risk* is equivalent to *probability; detriment* is equivalent to *probability* × *severity* (risk × severity). In the public perception of risk, however, the concept plays a more powerful role than one of mere chance [1]. Here the understanding of risk is "something you would like to avoid" or "the probability of something bad happening". It is often seen even as "something bad waiting to happen", but no one knows quite when or to whom. This perception may be responsible, in part, for the terms *risk* and *detriment* being used more and more interchangeably, even in technical literature [2].

To a large extent, risk has also been associated with technological advances in society. Technology has provided a means of progress, but with this, quite demonstrably, new risks have appeared. Thus, technology has become recognized not only as the *solution* but also as part of the *problem* of modern, industrialized society. An understanding that goes beyond the simple application of scientific and technological facts, provided by research to solve societal problems, has evolved. *Ineffective science, blundering technology* and *imperfect institutions* are the source of some societal risks, as indicated in the analysis [3] represented in Fig. 1.

2. RISK ANALYSIS, ASSESSMENT AND MANAGEMENT

The general framework in which risk studies are described and elements related recognizes that *risk assessment* is a process involving *risk analysis* and *risk evaluation.* Risk analysis itself requires the identification of the individual elements contributing to risk, *risk identification,* and some assignment of probabilities to these risk elements, *risk estimation.* This analysis of risk requires, in turn, combination

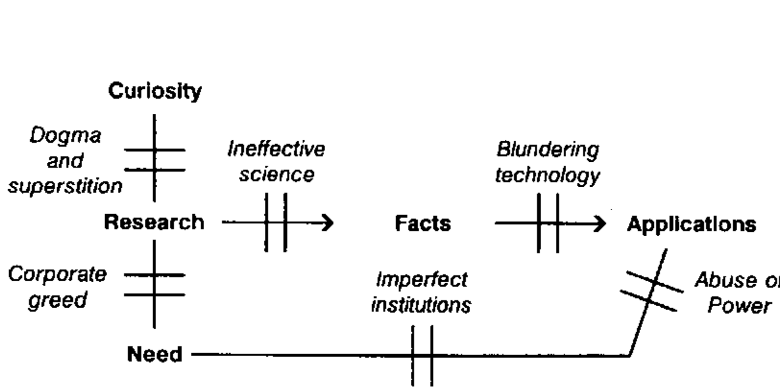

FIG. 1. Research, applications and system sources of man-induced risk [3].

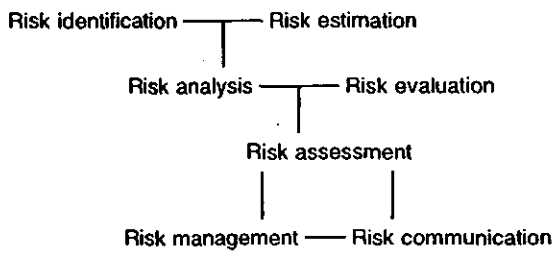

FIG. 2. Components of comparative risk studies [4].

with an evaluation or judgements, to give a *risk evaluation.* Only then is the risk analysis meaningful in any comparative or priority setting framework to produce a *risk assessment.* In risk evaluation, scientific and technical considerations are joined with social and political judgements, based on values. It is in the nature of risk studies that an element of social and political judgement needs to be included, since risk, by definition, depends, above all, upon a judgement that something is an ''*adverse* event or condition''.

Risk analysis, without the element of judgement leading to risk assessment, is incomplete, as it lacks the societal context which itself is the basis of the concept of risk. Furthermore, it is only from *risk assessment* that the process of *risk management* emanates and is operationalized. For such activities to address relevant problems and to be publicly acceptable, *risk communication* is an important activity. The relationships are displayed in Fig. 2.

3. COMPARATIVE RISK STUDIES

Comparative human health risk studies have been developed over a period of more than 25 years and have established a framework and set of methodologies that have allowed many assessments to be carried out. In contrast, the approach to comparative environmental risk assessment has been more diverse and less well developed, and still lacks any generally agreed conceptual framework, although many frameworks are in the course of development. Because of the progress in comparative human health risk methodologies it is fruitful to consider the direction of this work before dealing in more detail with environmental approaches.

3.1. Comparative human health risk assessment

Comparative human health risk studies have developed a framework that has allowed their use for a whole range of situations, including occupational health protection, radionuclide safety and the planning of electricity generation facilities, among others. Examples of the genesis of the approach may be found in many specialist and overview publications [5–20]. Generally, the method follows a sequence of *hazard identification — dose response estimation — exposure assessment — risk characterization;* a quantitative assessment of the risks involved facilitates comparison.

A definition of the system or systems under consideration, with clear system boundaries, is essential. Impacts may be *direct,* where exposure to harmful substances can be related to disability or death; or they may be *indirect,* acting through changes to other organisms or through harmful secondary products. Harm may result from an *accident,* from *acute* exposure (other than accidental) or from *chronic* exposure. The effects may be *immediate* or *delayed.* Exposures are usually differentiated between two main receptor groups: workers *(occupational exposure)* and the general public *(public exposure).* Exposure to combinations of hazardous substances may result in increased effects due to *additivity* or *synergisms,* or in reduced effects due to *antagonism.*

Evidence and quantitative estimates may be obtained from *direct observation* of exposure and disease incidence; disability or fatality frequencies linked to past exposures *(epidemiology); experimental studies* using test organisms; and *model*

TABLE I. HEALTH RISK OF THE COAL FUEL CYCLE EXPRESSED AS FATALITIES PER GW(e)·a [21]

Source	Nature of risk	Occupational	Public
Mining			
Underground	Immediate	1.2–1.67	—
	Delayed	0.26–1.46	—
Surface	Immediate	0.09–0.17	—
Transport			
Rail		0.00015–0.022	0.37–0.54
Truck	Immediate	0.014–1.23	0.6–2.4
Barge		0.062–1.0	0.07–0.28
Pipeline		0.16	
Conversion	Immediate	0.023–0.44	0.77
	Delayed	—	3.2–22

TABLE II. HEALTH RISK OF THE NATURAL GAS FUEL CYCLE EXPRESSED AS FATALITIES PER GW(e)·a [21]

Source	Nature of risk	Occupational	Public
Extraction			
Land based	Immediate	0.10–0.16	—
Offshore	Immediate	0.10–0.70	—
Processing	Immediate	0.0004–0.003	—
Transport	Immediate	0.009–0.02	0.2
Power generation	Immediate	0.009–0.018	—
	Delayed	Low	0.0025–0.017

simulations. Dose response relationships, inferred from the above, are important information, but it is also important to have estimates of the size of the receptor group to which a dose is committed (the *exposure commitment*). Effects from very low doses are difficult to determine and it is often impossible to distinguish between threshold relationships and linear no-threshold models.

Nevertheless, in spite of uncertainties, quantitative comparative health risk studies have been used quite frequently. Tables I and II give some estimates of health risk from specific activities for generating electricity from coal and natural gas; Ref. [22] gives data for oil, peat, oil shale, tar sands and nuclear power. Table III gives some comparative results. Figures 3–6 give some examples of comparative health risk.

3.2. Comparative environmental risk assessment

3.2.1. Overall frameworks

Sound comparative environmental assessments of risk are required to enable environmental impact priority actions to be set; to identify environmental research priorities; as an element in assessing the relative merits of planning and development actions; to help in the evaluation of the relative merits of alternative technology choices; to help in the establishment of guidelines for national environmental standards and as inputs to requirements related to international environmental agreements. However, the development of methodologies that allow comparative

TABLE III. SUMMARY OF FATALITY RATES (FATALITIES PER GW(e)·a) FOR DIFFERENT ENERGY SYSTEMS [23, 24]

Source	Occupational		Public	
	Immediate	Delayed	Immediate[a]	Delayed
Coal	0.4–3.2[b] 0.16–1.7[e]	0.13–1.1[c] 0.02–0.15[f]	0.1–1.0	2.0–6.0[d]
Oil	0.20–0.85[g] 0.22–1.35[h]		0.001–0.1	2.0–6.0[d]
Gas	0.10–0.5[g] 0.17–1.0[h]		0.2	0.004–0.2[d]
Nuclear (LWR)	0.09–0.5[b] 0.07–0.4[e]	0.13–0.37[b] 0.07–0.33[e]	0.001–0.01	0.005–0.2

[a] Applies to transport, being the major contributor to risk.
[b] Applies to underground mining conditions.
[c] Applies to underground mining, being the major contributor to risk.
[d] Applies to power plant operation, being the major contributor to risk.
[e] Applies to surface mining conditions.
[f] Applies to surface mining, being the major contributor to risk.
[g] Applies to land extraction.
[h] Applies to offshore extraction.

environmental risk assessments to be underaken has lagged far behind comparative human health risk assessments. The reasons for this are related to the multispecies nature of most environmental systems. This fact means that it is a far from simple matter to recognize one, or a few, criteria to which quantification can be applied in a straightforward manner. For human health risk comparisons, *mortality, morbidity, days of work lost* or associated *monetization* have been used.

A second consideration is related to the fact that interest in the detriment caused may be focused on ecosystem *structure, function* or both, or on one or several of the various elements of the ecosystem (soil, water, air or biotic components). Use has been made of *stress* or *pressure indicators* and *state* or *effect indicators* [25], leading to a *pressure — state — impact — response* approach [26]. This framework envisages an activity resulting in an agent for environmental change, such as gaseous

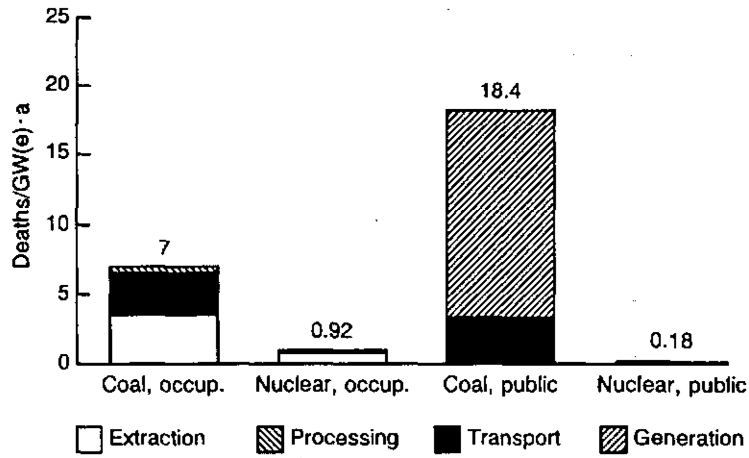

FIG. 3. Summary of health impacts from coal and nuclear fuel cycles — mortality [8].

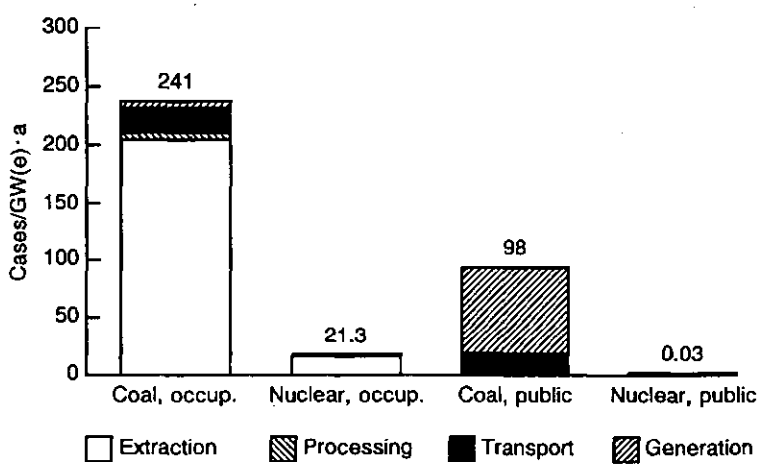

FIG. 4. Summary of health impacts from coal and nuclear fuel cycles — morbidity [8].

emissions or liquid effluents being discharged (pressure); this results in a certain physical state, such as atmospheric concentration of a gas or rate of deposition (state); the impact is the functional response to this, such as a reduction in yield or a change in soil pH (and associated changes); the response is the human reaction to the impacts. A system of *hazard identification — exposure assessment — effects assessment* has also been adopted in some work. All approaches have quantitative estimation difficulties and hence lack a sound comparative basis. It is a complicated

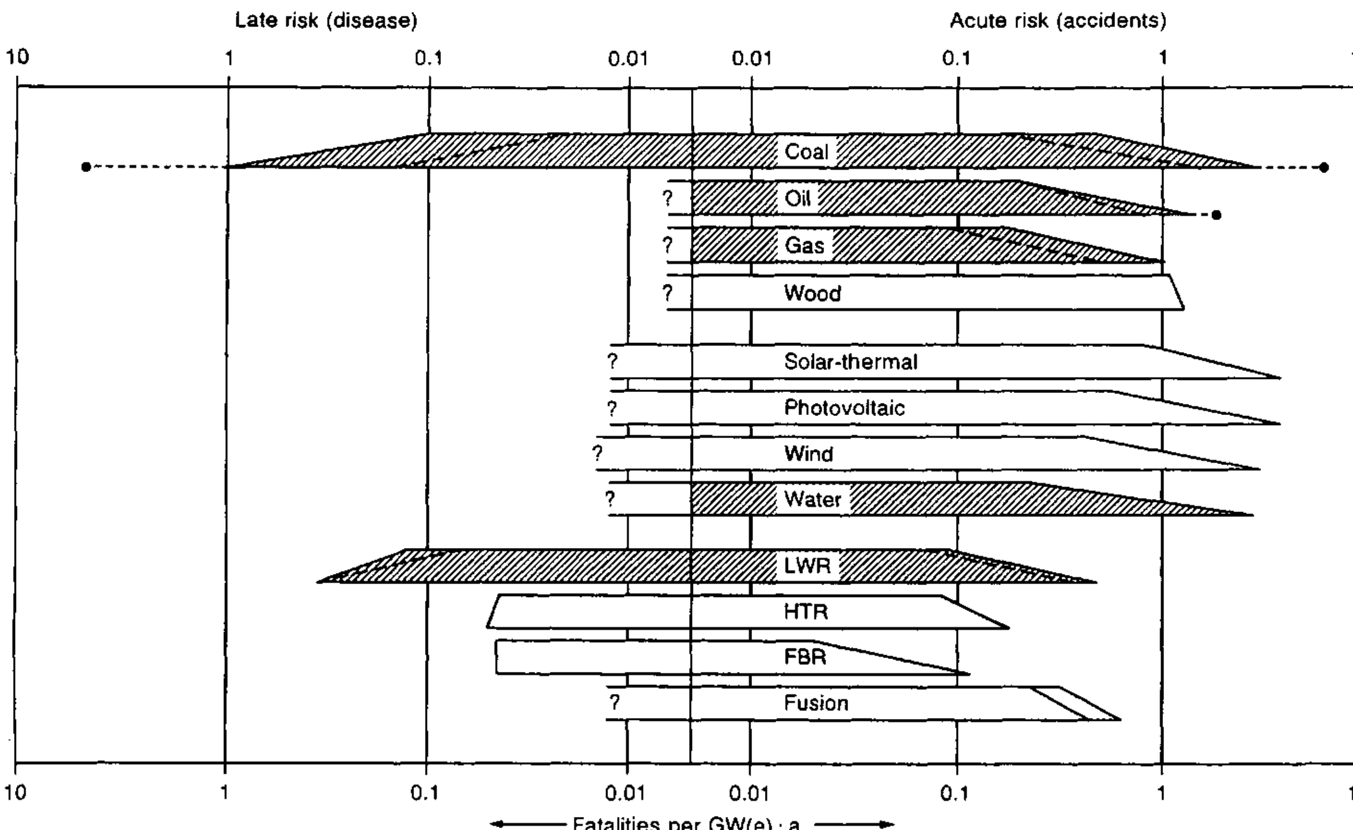

FIG. 5. Occupational mortality risks due to electricity production for all steps of the fuel cycle, without severe accidents [23, 24].

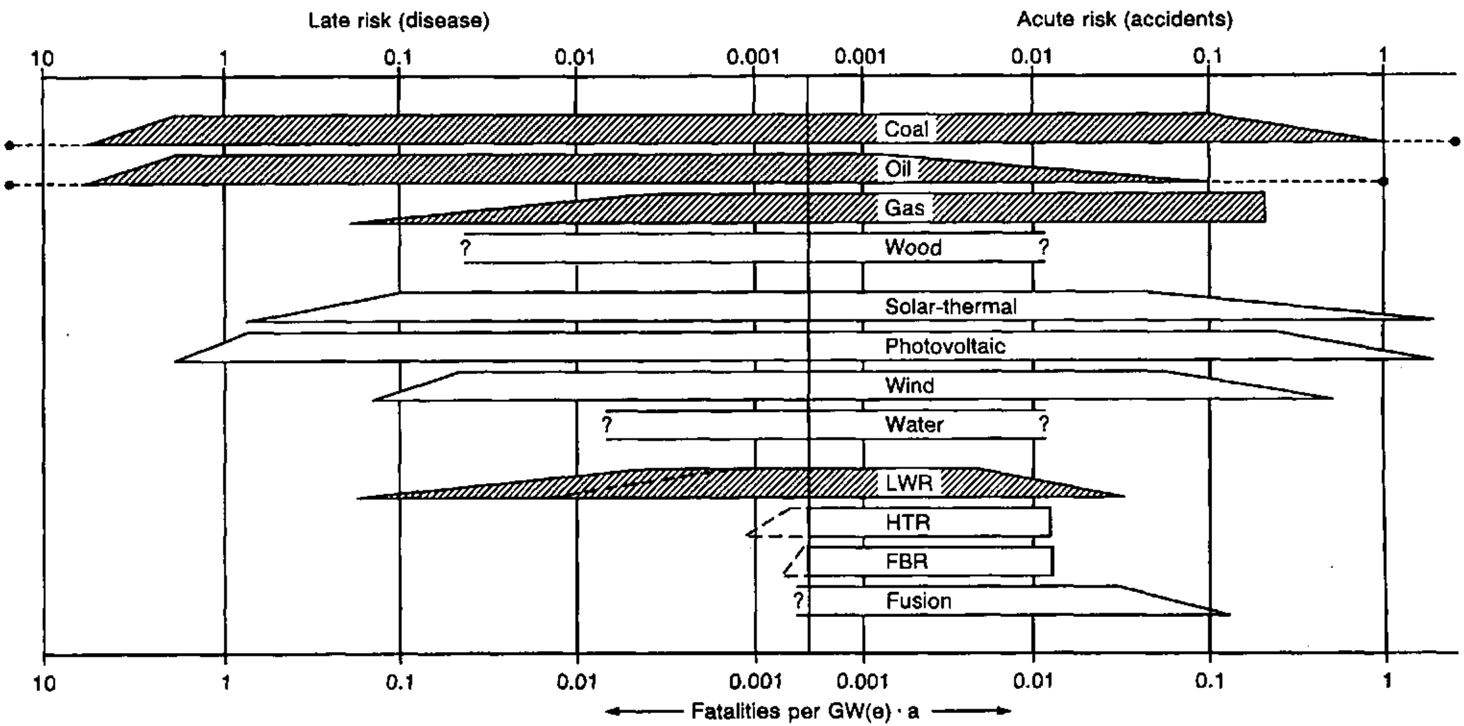

FIG. 6. Public mortality risks due to electricity production for all steps of the fuel cycle, without severe accidents [23, 24].

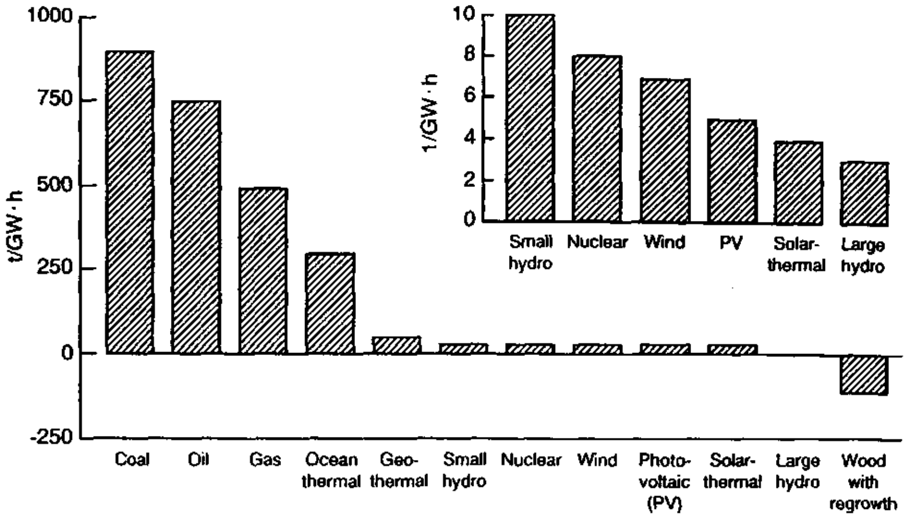

FIG. 7. Carbon dioxide emissions from different electricity generating technologies [27].

matter to find agreed criteria by which impacts may be assessed and compared because not only are the environmental effects not readily quantifiable but also there is no general agreement on what should be quantified.

A number of methods have been proposed to overcome this problem. One method is to use *ranked environmental assessments*. These have been well developed for environmental impact assessment (EIA) work. EIA can be regarded as a stepwise procedure to collect, organize, analyse and evaluate necessary information as a basis for planning and decision making regarding:

— the extent and character of a project,
— the background condition of the environment to be affected,
— the potential environmental effects in the future,
— the scope of the consequences for the people who will be influenced by the environmental effects of the project,
— the need for remedial measures.

An EIA often includes a preliminary assessment, called an initial environmental examination. Such early examination could serve as the basis for judging the necessary extent of an EIA. EIAs usually comprise a series of three analytical functions — identification, prediction and evaluation. Identification essentially revolves around characterizing the existing environment and those components of a development project which can have an effect on the environment. Prediction has the major objective of quantifying the identified impacts of a project action with respect to a common base and with respect to impacts from other project actions. Evaluation is the culmination of the EIA process, based on the previous two functions. It aids in communication of the appropriate information to decision makers about the possible alternatives and the impacts associated with each alternative, thereby facilitating informed decision making. Evaluation also enables a determination of groups that may be directly and indirectly affected by the project. Methods for displaying the *relative* importance (ranking) of impacts can be adopted and thus the major impacts evaluated and exhibited.

Emission values and ambient qualitative indices (actually pressure and state measures, respectively) have also been adopted and used to infer and compare potential impacts. This allows quantification and comparisons. An example [27] is given for carbon dioxide emissions for different electricity generating technologies (Fig. 7).

Critical loads or critical levels may also be employed [28]. When these are applied to ecosystem components — air, soil, water or other components — limits to environmental impacts above which damage would occur can be set. By obtaining estimates of how far these loads or levels might be exceeded (which may involve the use of integrated assessment models), a quantitative measure of the impact on the ecosystem may be obtained. Exceeding critical loads from place to place, or under a number of regimes, allows a comparison of environmental risk to be made (Figs 8 and 9). For example, comparison of the critical loads of acidity for sulphur (Fig. 8) with the amount by which these would be exceeded if the 1994 Oslo Protocol on Sulphur were to be fully implemented (Fig. 9) allows a comparative estimate of the degree to which areas are at risk from acidification.

3.2.2. Management based approaches

There are a range of approaches associated with comparative environmental assessment that are management based, spanning relevancy to sector, industry, process, product and customer concerns. At the sector and industry end, the methods range from *fuel cycle analysis* (FCA), through *life cycle assessment* (LCA) and *environmental priority strategies* (EPS) at the process-product interface, to product-customer orientated methods such as *life cycle costing* (LCC) and *quality function deployment* (QFD). More general approaches include *catchment analysis, cost-benefit analysis* and *integrated environmental assessment* (IEA).

LCA is the only management method that currently covers all aspects of materials, energy and products that need to be identified, quantified and evaluated for a process [29]. To make full use of LCA in practical product development, it is considered that LCA should be integrated with other approaches such as QFD and LCC *to yield a green integrated product development method.* This has yet to be implemented or achieved.

LCA has been defined as an objective process to evaluate the environmental burdens associated with a process, product, activity or service system by identifying

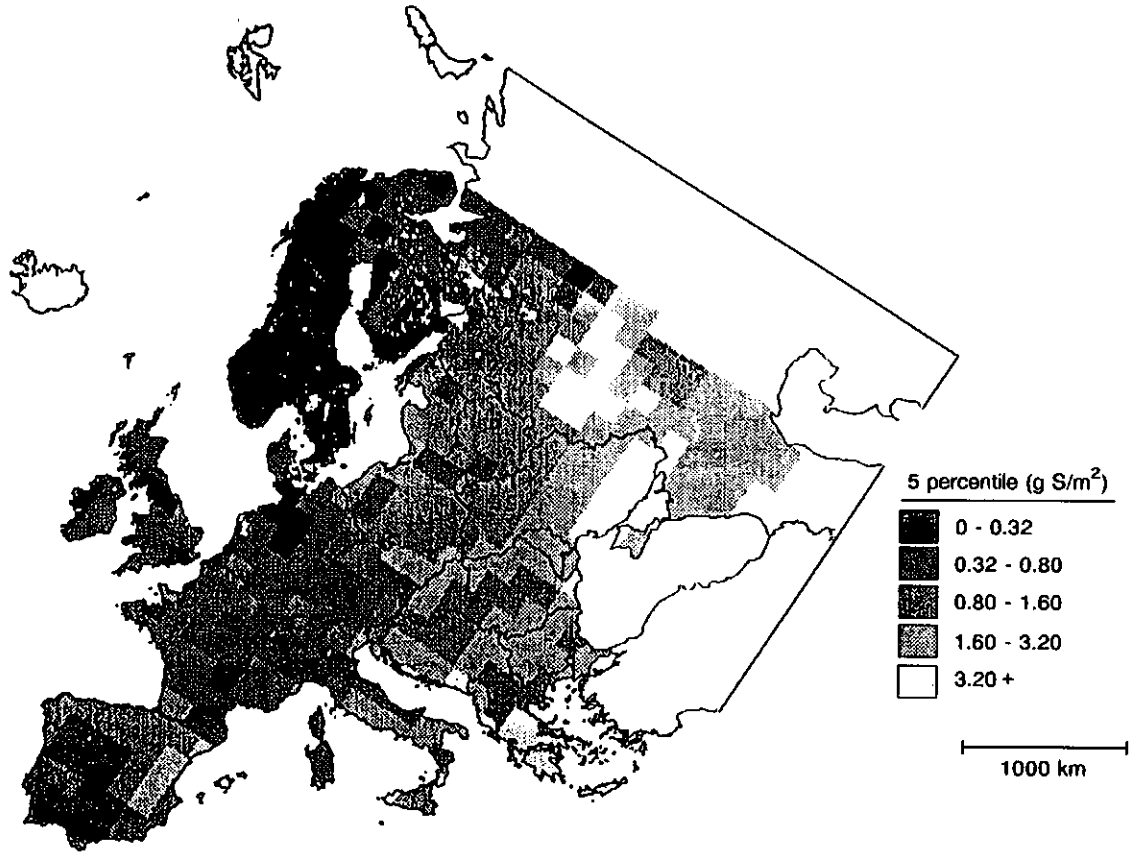

FIG. 8. Critical sulphur deposition (5 percentile) for Europe.

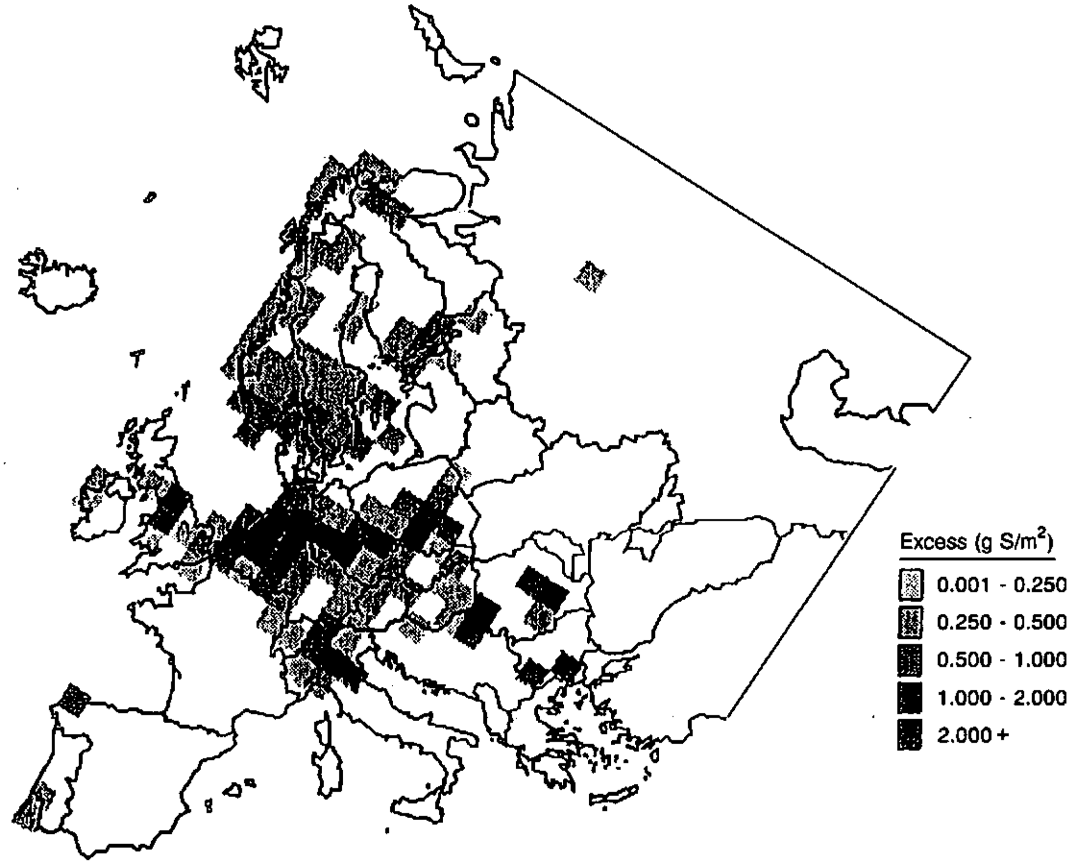

FIG. 9. Transgression of critical loads under the Oslo Protocol (2010).

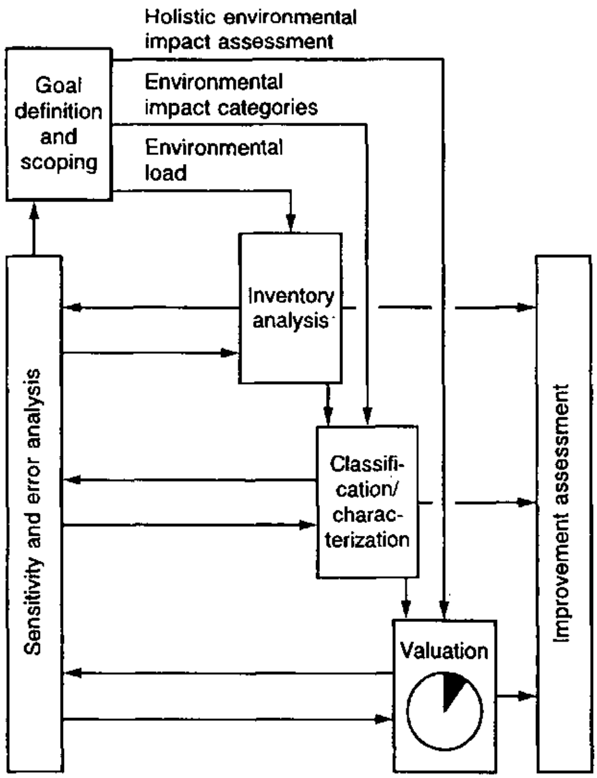

FIG. 10. Life cycle assessment framework.

and quantifying energy and materials used and released to the environment, to assess the impact of those energy and material uses and releases to the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the process, product, activity or service system, encompassing extracting and processing raw materials, manufacturing, transportation and distribution, use, reuse, maintenance, recycling and final disposal.

The LCA methodological framework is a stepwise calculation exercise comprising four components: *goal definition and scoping, inventory analysis, impact assessment* and *improvement assessment* (Fig. 10). Since each of these components is part of a broader methodology, the use of a single one cannot be described as an LCA, which ought to include all four components. In many cases, life cycle studies focus on inventory analysis and are usually referred to as *life cycle inventory* (LCI).

In many general programmes for cleaner production strategies, design for the environment or environmentally sound product development, the principal objective is often to lower the overall environmental impact during the life cycle of a product. To meet these demands it is sometimes necessary to arrive at a highly aggregated form of the EIA, which in turn emphasizes the need for identifying a generally accepted valuation approach for a scoring system to weigh the different environmental effects against each other.

The *scope* of an LCA defines the system boundaries, data requirements, assumptions and limitations. The scope should be defined well enough to ensure that the breadth and depth of analysis are compatible with, and sufficient to address, the stated purpose and all boundaries, and that assumptions are clearly stated, comprehensible and visible. However, as LCA is an iterative process, it may be that in some cases it is not recommended to permanently fix all aspects included in the scope. The use of *sensitivity and error analysis* is recommended in order to enable successive testing and validation of the purpose and scope of the LCA study versus the results obtained for corrections and setting new assumptions.

Inventory analysis is an objective, data based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste and other environmental releases incurred throughout the life cycle of a process, product, activity or service system (Fig. 11).

The calculation of inputs and outputs in the inventory analysis refers to the system defined. In many cases, few processing operations yield a single output, while it is important to break down such a complex system into a series of separate subprocesses, each of which produces a single product. During the production of a construction material, there are pollutant emissions from the various sub-processes, from raw material acquisition to the final product. The total production process may

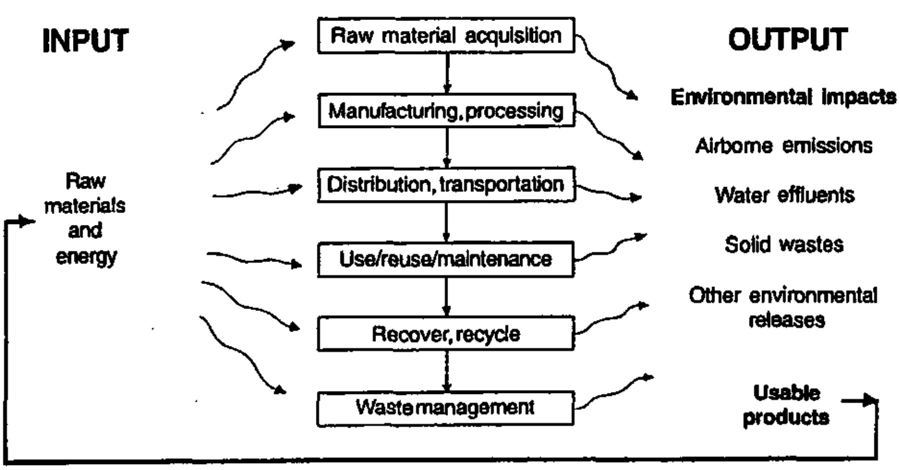

FIG. 11. Scope of inventory analysis.

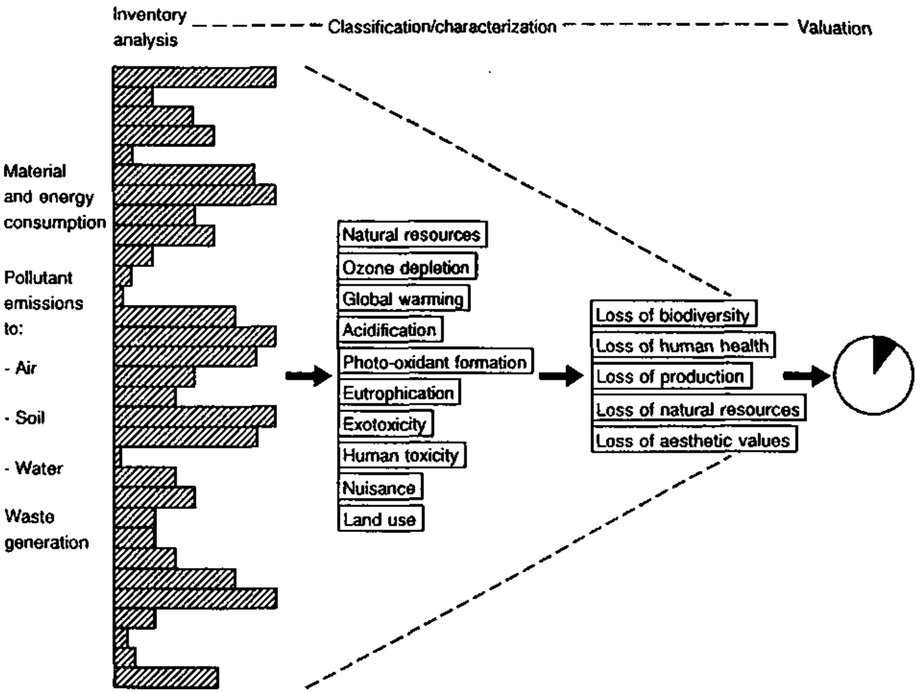

FIG. 12. Relationship between inventory analysis and components of impact assessment.

be illustrated by a 'process tree', where the stem may be seen as the main chain of flow of materials and energy, whereas the branches may illustrate sub-processes and the leaves the specific figures on pollutant emissions. When added together, these sub-processes have the same total characteristics as the original single system of co-products.

It is recommended to obtain estimates of the accuracy of the data gained in the inventory analysis in order to enable a sensitivity and error analysis. All data used should therefore be 'labelled' with relevant information, not only on reliability but also on source and origin, to facilitate updating and refinement of the data (so-called meta-data). The use of a sensitivity and error analysis will identify the key data that are of great importance for the outcome of the LCA study, which may need further efforts to increase its reliability.

Impact assessment is a technical, qualitative and/or quantitative process to characterize and assess the effects of the environmental loading identified in the inventory analysis component. The assessment should address both ecological and human health considerations, as well as other effects such as habitat modifications and noise pollution. The impact assessment component could be characterized as three consecutive steps — classification, characterization and valuation — all of which interpret the effects of environmental burdens identified in the inventory analysis, on different aggregated levels (Fig. 12). *Classification* is the step in which the inventory analyses are grouped together into a number of impact categories; *characterization* is the step in which analysis and quantification take place and, where possible, aggregation of the impacts within the given impact categories is carried out; *valuation* is the step in which the data of the different specific impact categories are weighted so that they can be compared amongst themselves to arrive at a further interpretation and aggregation of the data of the impact assessment.

In the classification step, the impacts may be grouped into the general protection areas of resource depletion, ecological health and human health. These areas may be further divided into specific impact categories, preferably focusing on the environmental processes involved, to enable a perspective consistent with the current scientific knowledge about these processes.

There are various approaches to characterization: to relate data to no-observable-effect concentrations or to environmental standards; and to model both exposure and effects and to apply these models in a site specific way or to use equivalency factors for the different impact categories. A further approach is to normalize the aggregated data per impact category to the actual magnitude of the impacts in a given area in order to increase the comparability of the data from the different impact categories.

Valuation, with the aim of further aggregating the data of the impact assessment, is perhaps the LCA component that has been subject to most of the heated LCA debates. Some existing approaches, often referred to as decision theory techniques, are claimed to have the potential to make the valuation a rational, explicit method. The subject for controversy is often due to the aggregation leading to a single number or an index. A single number or an index represents the end-point of the impact assessment — a holistic evaluation of the total environmental impact during a life cycle of the object in focus for the study. However, an index may also represent a holistic environmental impact per mass, volume or area for material or processes. Indexation of environmental impacts is of great value to make LCA practical for use in daily work with product development.

There exist a number of different valuation principles resting on scientific, political or societal judgements. Essentially, most of them fall into the following categories or are a combination of the approaches to:

— a distance-to-target sustainable or political level,
— energy or cost for reduction (per process),
— willingness to pay for reduction/prevention (per problem),
— methods involving panels.

Such considerations also differ with regard to spatial resolutions. While the distance to target usually relates to a country specific approach, the willingness to pay may relate to a regional or global approach.

Of special importance is the use of sensitivity and error analysis. Sensitivity analysis enables identification of those selected valuation criteria that may change the resultant priority between two process or product alternatives because of the uncertainties of the data. Error analysis may be used to indicate the significance of one alternative product being more environmentally benign than a competing product.

Many are of the opinion that valuation has to be based largely on information about social values and preferences. However, no one has yet defined the specific requirements that a reliable and generally accepted valuation method should meet. It should be clearly emphasized that any valuation system for assessing the 'seriousness' of the environmental impacts of any human activity must be largely based on subjective value judgements. The establishment of criteria for such valuations that are tenable in all situations worldwide is unlikely.

Improvement assessment is a systematic evaluation of the needs and opportunities for reducing the environmental burden associated with energy and raw material use and waste emissions throughout the whole life cycle of a product, process or activity. This assessment may include both quantitative and qualitative measures of improvements, such as changes in product design, raw material use, industrial processing, and consumer and waste management.

The improvement assessment component has been identified as the part of LCA that is least well documented. However, preliminary results from some large LCA studies carried out have all indicated that significant environmental burdens from products seem to be linked to the product use. Hence, there seems to be a potential for industry motivated initiatives to minimize environmental impacts through product development.

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INTEGRATED ECONOMY/ENERGY/ ENVIRONMENT MODELS

P. CAPROS
National Technical University of Athens,
Athens, Greece

Abstract

INTEGRATED ECONOMY/ENERGY/ENVIRONMENT MODELS.

The paper presents a review of alternative methodologies in the field of economy, energy and environment (E3) modelling, with particular emphasis on the computable general equilibrium approaches, and the newly developed models of the European Commission (EC). The GEM-E3 model (general equilibrium model for economy, energy and environment), developed for the EC (DG-XII/F1) by a consortium involving the National Technical University of Athens (NTUA), the Centre for Operations Research and Econometrics (CORE), the Katholieke Universiteit Leuven (KUL), the University of Mannheim and the Commissariat à l'énergie atomique (CEA), follows the computable general equilibrium methodology based on the Arrow-Debreu theory. The model considers multiple production sectors, multiple economic agents and multiple countries (European Union, EU), which interact through perfectly competitive markets for goods, labour and capital. The output of the model includes full input-output tables, national accounts, employment, trade, monetary and other macroeconomic variables for all EU countries. GEM-E3 considers explicitly the energy sectors, abatement costs, atmospheric pollutants (including CO_2) and related policy instruments (taxes, pollution permits, etc.). The model is designed to provide a general purpose tool for macroeconomic analysis and for the study of economic implications of energy and environment strategies. The model operates dynamically along a path of general equilibrium solutions. The energy model PRIMES (price induced model of the energy system), developed for the EC (DG-XII/F1) by a consortium involving NTUA, CORE, KUL, the Institut Français du Pétrole (IFP), the Belgian Company COHERENCE and the Energy Technology Support Unit (ETSU) of the Harwell Laboratory, also follows a market oriented approach. PRIMES is a detailed energy system model with an explicit representation of technologies. It is modular, consisting of energy demand and supply sub-models. Each sub-model reflects the energy related economic decisions of an agent (demander and/or supplier). The sub-models interact within a set of energy product markets that may be governed by alternative market clearing regimes. These interactions determine energy prices and ensure equilibrium between energy demand and supply. PRIMES follows a very detailed nomenclature for energy products and technologies and covers the EU countries.

1. OVERVIEW OF ECONOMY/ENERGY/ENVIRONMENT MODELLING APPROACHES

The objective of economy/energy/environment (E3) modelling is to study the interactions between macroeconomic, energy and environment systems, linked through a closed loop. The discipline originated in the 1970s through economy/energy modelling and the seminal work of several modellers, for example Hudson and Jorgenson [1, 2] and Manne [3]. A natural extension of E3 modelling is the incorporation of environmental mechanisms, considering implications for the biosphere, abatement costs and externalities. Integrated models include specific system models for the three parts of E3 and formulate effects and feedback. Integration does not necessarily mean uniformity in the modelling approaches for the three parts. The development of integrated E3 models is still challenging the research community because of their methodological, computer and mathematical complexity.

Methodological paradigms are currently dominated by the economic general equilibrium theory. Through such an approach, projections and counterfactual model simulations can be interpreted for normative policy analysis (contrary to descriptive approaches).

1.1. New challenges for E3 modelling

During the last five years, the emergence of the global climate change threat from energy related emissions of CO_2 has triggered highly qualified research on modelling the interactions between economy, energy and environment systems.

Earlier work in this field was concerned with modelling energy/economy interactions in the context of energy supply shortages or high prices. Between 1974 and 1983, this led to the development of an important range of modelling techniques and methodologies, such as the general equilibrium modelling of Jorgenson and the system optimization models of Manne and others (for a tutorial on the different techniques used in energy systems analysis, see Ref. [4]).

The new issues related to CO_2 emission reduction are more challenging, since they imply:

— More complexity because global economy, energy and environment systems are affected;
— More uncertainty because it is necessary to deal with a longer term horizon and a change of technology;
— More difficulty because of the need to represent decentralized decisions in a market oriented paradigm (in contrast to Government planning), since current problems occur in the context of accelerated market liberalization worldwide.

Satisfying these three requirements in a single empirical model still remains a challenging mathematical and computational problem. All the available empirical models in the field focus on one or two of the above requirements, while substantially neglecting the third one, in order to reduce the computational burden. For example, detailed technological models satisfy the second requirement but often neglect market related decentralized behaviour of agents and cover only the energy/environment systems. Macroeconomy oriented models may well represent market orientation, through the economic equilibrium paradigm, but they often neglect the aspects of technological change and details of energy systems. Finally, growth models, which cover the long term evolution of the economy and deal with technological change, often neglect the individual behaviour of agents in a market context.

This situation limits the possible insight into new issues. It is necessary to combine approaches and models, to reconcile results and to work with a synthesis of partial conclusions.

1.2. *Limitations of older approaches*

Earlier detailed technological models are usually characterized as bottom-up approaches. They are usually based on a mathematical programming (optimization) problem which covers the energy system or even the economy/energy/environment system. In the former case, the models (for example EFOM [5], MARKAL [6] and BESOM [7]) are mainly used for energy technology characterization and forecasting in the context of a perfect market. In the latter case, the models (for example ETA-MACRO [3], Goulder's model [8], Global 2000 [9], ERM [10] and DICE [11]) are usually driven by the economic growth theory and are used to study the implications of technology changes and CO_2 mitigation options for long term economic growth.

The above types of models are often criticized for their lack of explicit representations of markets, related policy instruments and individual behaviour of agents. The so-called 'efficiency gap' problem illustrates this point. The bottom-up approaches identify the existence of an energy efficiency potential that may be achieved without extra cost to the system (a sort of free resource). However, in reality there is no evidence of the existence of such an efficiency potential (this is called the 'efficiency gap' [12]). Microeconomic analyses suggest that this gap can be explained by specific conditions that prevail in the markets (distortions, barriers, etc.) and by the different behaviour of economic agents (for instance, small consumers may use high subjective discount rates).

1.3. The emergence of market oriented modelling approaches

The above mentioned points as well as the need to represent the growing process of market liberalization have motivated analysts to adopt market oriented modelling approaches that involve explicitly market regimes and model separately the behaviour of economic agents. Such models can incorporate detailed representations of policy instruments and structural options that can alleviate the efficiency gap problem. They are often called 'new generation models' and currently prevail in policy analysis studies.

Examples of such energy/environment system models are the intermediate future forecasting system (IFFS) [13], the generalized equilibrium modelling system (GEMS) [14], GEMINI [15], ENPEP [16], the national energy modelling system (NEMS) [17] (all from the United States of America) and PRIMES [18] (from the European Commission, EC). These models are often characterized as partial equilibrium models because they cover only the energy system and not the rest of the economy. They are also known as generalized equilibrium models because they can describe different behavioural circumstances of economic agents by using different mathematical formulations for the sub-models, and they can describe different market clearing regimes by using different algorithms for global convergence (equilibrium).

Similar aims led analysts to propose general equilibrium models that consider the whole spectrum of economy, energy and environment interactions based on market oriented formulations. This trend connected, as expected, the independent efforts of economists in the field of 'pure' macroeconomic models. In this field, one can find the various macroeconomic paradigms that dominated the modelling activities of economists, mainly the neokeynesian and the neoclassical approaches (see Ref. [19]). The neokeynesian approach accepts disequilibrium conditions in the markets and can provide projections for the short/medium term (for example HERMES [20]). The neoclassical approach, which dominates current development work, formulates price driven market equilibrium regimes and allows for a normative characterization of policies and structural change (for example computable general equilibrium models, such as those developed within World Bank activities [21]). The nature of policy issues concerned with economy/energy/environment interactions requires a computable equilibrium approach, for several reasons: structural change is involved in market regimes and technology; the market competition paradigm prevails in current policy analysis, as mentioned previously; and policy measures must be evaluated by considering comparable projections (since all projections attain general equilibrium).

1.4. Modern E3 models

The attractiveness of computable general equilibrium models inspired analysts to extend the models to include more details (or new sub-models) covering the interactions with the energy sector and the environment. Through these extensions, general equilibrium is achieved simultaneously for all three systems. This is achieved by assuming the following points:

— All markets clear simultaneously, for example markets for goods, labour, energy and pollution permits;
— The optimization behaviour of suppliers incorporates the costs and constraints from environmental policies (abatement, policy limits, taxes);
— The optimization behaviour of consumers incorporates the environmental dimension, involving costs and damages, which generally influence the consumer's utility;
— The energy sector contains engineering details, for example on electricity supply;
— The policy instruments considered for energy and environment policies are explicitly included in the model so as to support policy analysis.

The pioneering work along these lines was provided by Jorgenson (DGEM model [22]); the models GREEN [23], GEM-E3 [24] and other models were built more recently.

1.5. Integrated assessment approaches

For the analysis of global climate change issues, particularly for the long term, the method of integrating the environmental system representation in the economic model is of importance. The effects of a climate change on the economy are particularly difficult to evaluate because of the complexity of environmental changes and the global nature of the interactions. This difficulty triggered the development of global assessment models that attempt to establish detailed links, from the emissions to the economic valuation of damages, taking into account global climate change. In addition to the economic equilibrium model, these approaches integrate models for geophysical simulation including geographic specificity, for example IMAGE [25], MERGE [26] and DICE [11].

From an economic point of view, however, two problems arise regarding the integration of environmental effects in the economy:

(1) The formulation of utility (or welfare) changes induced by degradation of the environment, which is a challenging problem; and
(2) The valuation of damages, in other words the quantification of externalities.

For the latter, several accounting procedures have been proposed, which usually link physical damages to health, living conditions and society, for example the ExternE project of the EC [27].

1.6. Categorization according to model use

The way in which economy/energy/environment models are used in practice has important implications for their formulation. We consider a general distinction between general purpose models, developed not only for climate change analysis but also for policy analysis, and models specifically developed for the climate change issue. The latter models are generally more simplistic than the former ones, particularly with respect to policy instruments and their representation of technology assumptions and the economy. The climate change models have to cover the global character of climate change mechanisms, together with economic growth and technology evolution over very long periods.

The general purpose models are more detailed and realistic; they cover a shorter time horizon but are not able to fully represent the longer term restructuring and feedback effects relevant to climate change. The treatment of the backstop technology illustrates these points. This is considered to be a non-identified technology, possibly carbon free, that has to replace current technologies in the very long term so as to achieve global objectives. All long term models specific to climate change issues use the concept of a backstop technology (or fuel) and most of the conclusions are mainly attributed to this technology and depend heavily on its numerical characteristics (this tends to be independent of the approach of the model, for example MERGE and GREEN). On the contrary, in general purpose models the concept of a backstop technology does not exist, since it cannot be identified with current knowledge. Therefore, these models do not exploit the likely full potential for CO_2 mitigation; on the other hand, they do not rely on such uncertain information.

1.7. The experience of the EC

The work supported by the EC is characterized by trends in the modelling field similar to those described above.

The older models of the EC were built for specific purposes, different from those currently requiring integrated assessment approaches. The EFOM model was a detailed technological model for the energy system and followed a general system optimization methodology. To study acid rain policies, the model was extended by provision of pollution abatement modules for all energy activities and increased technological detail. As the CO_2 mitigation issue became politically important, the EFOM model (CRASH programme of DG-XII [28]) provided an analysis of the technological change needed to support CO_2 objectives. This is one example of the studies in which the energy efficiency gap was estimated, as mentioned before. In parallel to EFOM, and mainly to meet the needs of macroeconomic policy analysis, the HERMES model was developed, following a rather traditional neokeynesian methodology. It was first used for internal market studies and then for studies of the macroeconomic consequences of carbon taxes and related policy measures.

The MIDAS energy model [29] was the first EC model that provided a separate representation of the behaviour of agents (energy demanders and suppliers) and formulated explicitly cost/price setting mechanisms. However, there was no explicit treatment of competitive market regimes, apart from monopolistic competition regimes. MIDAS was highly detailed on the supply side but econometric on the demand side. For this reason, MIDAS was used mainly for smooth projections and scenario construction; it was the main model used for analysis of the implications of carbon tax policies.

Following the general trend, the EC reoriented its modelling work towards the market competition paradigm, both for the energy (PRIMES) and the economy (GEM-E3). PRIMES follows the generalized equilibrium methodology to model the energy system; GEM-E3 adopts the computable general equilibrium approach with integrated feedback mechanisms for all three systems, namely economy, energy and environment. Both models were conceived specifically for the study of climate change strategies as well as for other purposes. They do not consider the very long term or integrated assessment that is required for global analysis; however, they include economic valuation of damages. Both models fully support the need to study technology and economic policy in the context of growing competition between markets.

Over the next two years, the EC will launch a new integrated study dealing with the analysis of climate strategy and technology policy within competitive markets. This study will use the market oriented models mentioned above to set up a normative strategy for technological development and adequate accompanying measures in order to create a new growth potential that is sustainable with respect to climate change constraints. The main issue is to set up such a policy in the context of liberalized markets, so as to ensure consistency with individual behaviour and market regimes. The policy measures to be considered are characterized according to the general concept of internalization of externalities. The latter will be appraised when the results of the ExternE project (DG-XII) are available.

2. THE GEM-E3 MODEL

2.1. General presentation of the model

The GEM-E3 model is an operational, empirical model that follows the computable general equilibrium methodology. The model aims at representing the interactions between the economy, the energy system and the environment. It clears the market at both the country specific level (EU Member States) and the Europe-wide level.

The general structure of the macroeconomic core of GEM-E3 is illustrated in Fig. 1. The model has the following features:

- It represents multiple sectors and multiple countries;
- It clears simultaneously the markets of commodities and primary factors (labour, capital);

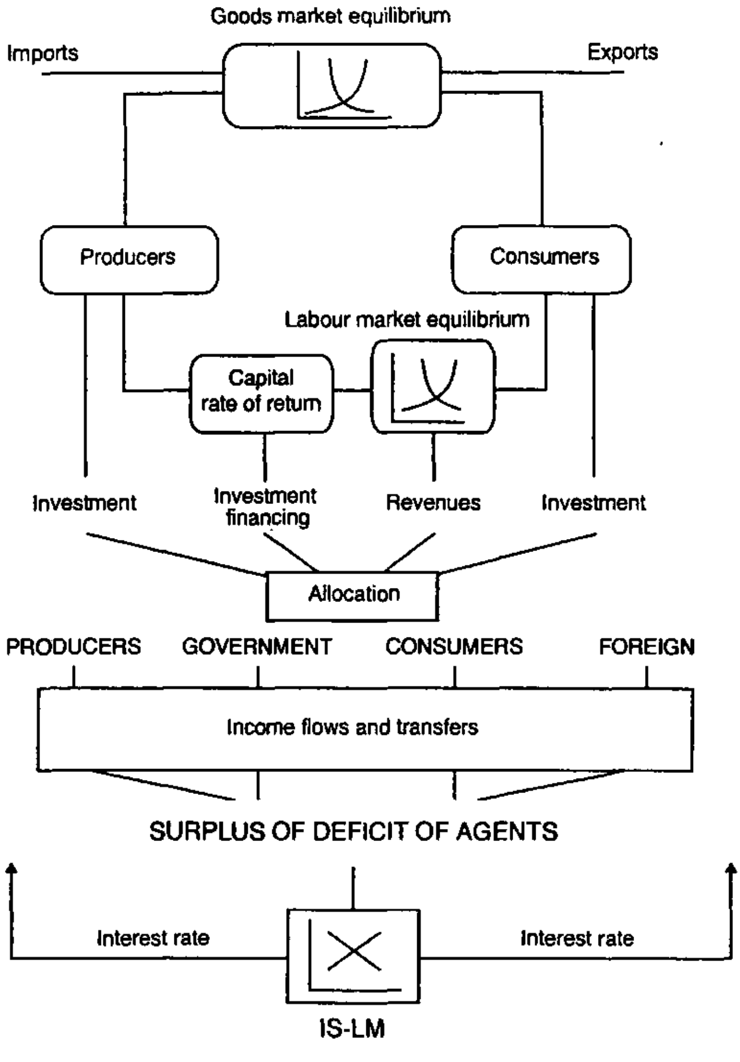

FIG. 1. General scheme of the model.

— It represents energy forms and environmental policy instruments;
— It computes explicitly the equilibrium prices for the above markets so that it is able to support policy analyses of taxation and alternative market clearing regimes;
— The formulation of behavioural equations and the closure rule are such that the model simulations cover both the medium term and the long term;
— The capital stock is fixed within a year, but it accumulates over time through endogenously driven investment;
— A set of other mechanisms, such as stock flow consistency and backward looking anticipation, complete the dynamics of GEM-E3.

The model considers simultaneously the EU countries linked together and these countries linked with the rest of the world. The model is constructed as a single system of equations that incorporate simultaneously the equilibrium markets of all European countries. Endogenous foreign trade links the countries so that they form a closed loop. This is formulated in a way which ensures, in all cases, equality between the imports of one country and the corresponding exports of another country (in volume and value) — a condition that corresponds to a trade matrix and to zero trade deficit (in value) at the global level.

The model provides three axes for use in policy analysis: (a) sustainable economic growth (with respect to the environment), (b) an internal European market (for economy and energy), and (c) European perspectives within an evolving international context (for both economy and energy).

A major benefit of using GEM-E3 in support of policy analysis is the consistent evaluation of distributional effects, across countries, economic sectors and (in the next future) social groups. The burden sharing aspect of environmental protection is thus fully analysed, while ensuring that the European economy remains at general equilibrium conditions.

2.2. Domestic production

Production functions exhibit a nested separability scheme, involving capital (K), labour (L), energy (E) and materials (M). Energy is further divided into electricity (El) and other fuels.

First, production is split into two aggregates, one consisting of capital stock and electricity, and the other consisting of the aggregate of labour, materials and other fuels. Second, the two ensuing production functions are further divided into their component parts. The constant elasticity of substitution (CES) specification is used throughout. Figure 2 illustrates the nesting of the production functions.

The model formulates the domestic supply of goods through the above production functions and assumes a constant return of scale and exogenous rates of technical progress. At the equilibrium point, the derived demand for production factors

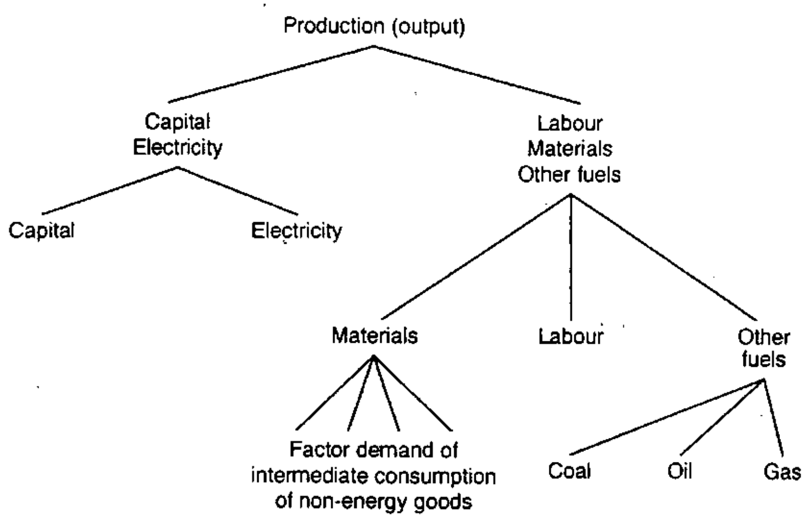

FIG. 2. Domestic production functions.

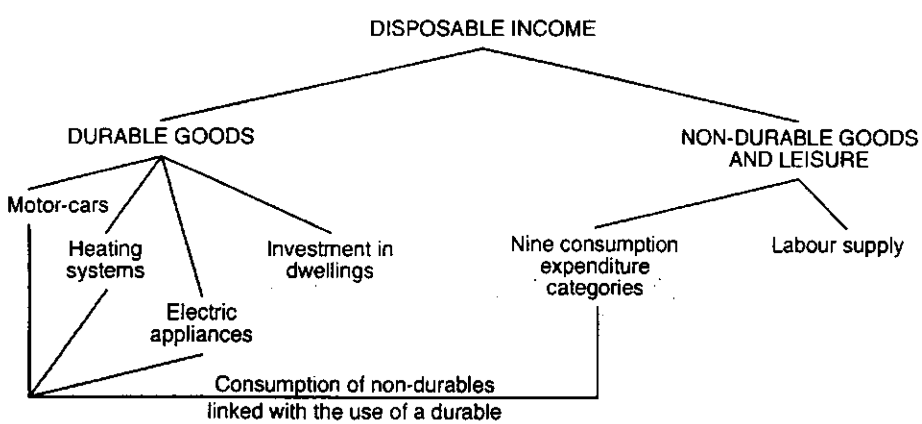

FIG. 3. Final consumption scheme of households.

(labour, energy, material, capital services) is such that all sectors maximize profits at zero-profit level. Capital is considered to be fixed in the short term; therefore, the supply function is positively sloped, exhibiting diminishing returns. Capital is accumulated dynamically through investment.

2.3. Final consumption of households

The decisions in households concern, first, income and leisure so as to maximize an inter-temporal utility function under an inter-temporal budget constraint. Then, the income is further divided into consumption, investment in physical assets (dwellings) and investment in monetary assets (savings). Finally, the total consumption is divided into demand categories through a linear expenditure system that covers all durable and non-durable goods. The demand for consumption categories is then transformed into a demand for products by means of a transition matrix with fixed technical coefficients. Figure 3 presents the general separability scheme of the consumption of households.

Households consume a range of durable goods (cars, heating systems, electric appliances and investment in dwellings) and non-durable goods, which are grouped into consumption categories (food, culture, etc.). Durable goods demand the consumption of some non-durable goods (e.g. cars consume gasoline). Therefore, non-durable goods are linked to the stock of durable goods; these are electricity, oil, motor fuels and other fuels. For all durable goods it is assumed that they use a fixed proportion of energy sources.

Finally, labour supply is also determined within this module, as derived from preferences for leisure.

2.4. Foreign trade

The model does not cover the whole planet and thus the behaviour of the rest of the world (ROW) is left exogenous. However, the EU Member States are endogenously linked through trade of goods and services.

The exogenous imports demanded by the ROW are flexibly satisfied by exports originating from the EU countries. The latter, however, consider the profitability of exporting to the ROW, exporting to the EU or addressing the goods to their domestic markets. Through these profitability considerations, the EU countries set their export prices. A modified export supply function represents these mechanisms, following a constant elasticity of transformation (CET) formula.

Imports demanded by the EU countries from the ROW are supplied flexibly by the latter. However, the EU countries consider the optimal allocation of their total imports across the countries of origin, according to the relative import prices. The EU countries buy goods at the prices set by the supplying countries, following their export supply behaviour. Of course, the supplying countries may gain or lose

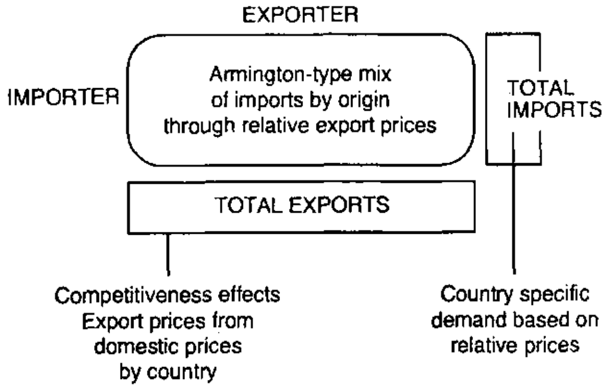

FIG. 4. Trade matrix for the EU and the ROW.

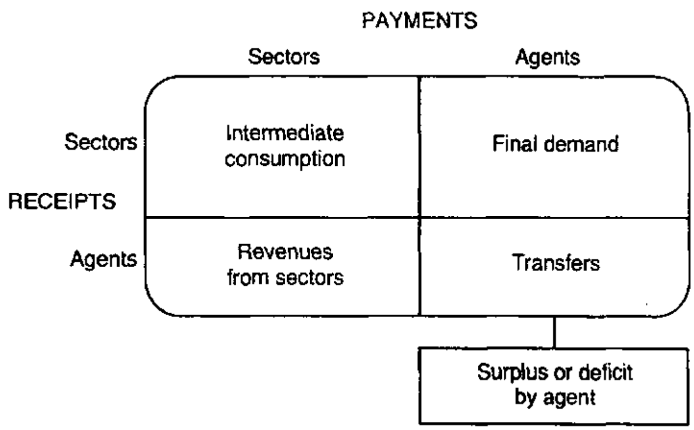

FIG. 5. Social accounting matrix.

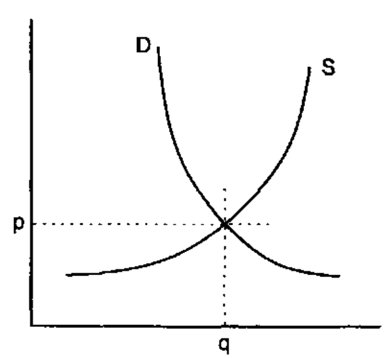

FIG. 6. Equilibrium of the real part.
D — demand, S — supply, p — prices, q — quantities.

market shares according to their price setting. When importing, the EU countries compute an index of mean import price according to their optimal allocation by country of origin. This mean import price is then compared with the domestic prices in order to allocate the demand for imports and domestic production. A nested two-level Armington function represents this mechanism.

A trade flow from one country to another matches, by construction, the reverse flow. The model ensures this symmetry in volume, value and deflator. Thus, it is obvious that the model guarantees (in any scenario run) all balance conditions applied to the world trade matrix, as well as the Walras law at the global level. Of course, all of these are validated on the same currency basis, namely the ECU.

Figure 4 illustrates the trade matrix for the EU and the ROW.

2.5. Income accounts

The real sector of the model is grouped within the framework of a social accounting matrix (SAM) (Fig. 5), which ensures consistency and equilibrium flows from production to the agents and back to consumption. The construction of the SAM is the starting point for building the model. The definition of the set of prices ensures the consistency of the SAM (in present currency). This is reflected by the above condition, which states that the algebraic sum of net savings over the set of agents is, by construction, equal to zero.

The economic agents are households, firms, Governments and the ROW. The sources of income for consumers and producers are labour and capital reward. The sources of income for the Government are transfers and taxes. The agents use the income for consumption or investment. Finally, the surplus or deficit by an agent equals the net savings minus investment.

2.6. Equilibrium of the real part

The equilibrium of the real part is achieved simultaneously in the goods market and in the labour market. Figure 6 presents the equilibrium of the real part for both markets.

In the goods market a distinction is made between tradable goods and non-tradable goods. for the tradable goods the equilibrium condition refers to the equality between the supply of the composite good, related to the Armington equation, and the domestic demand for the composite good. This equilibrium, combined with the sales identity, guarantees that total resource and total use in value for each good are identical. For non-tradable goods there is no Armington assumption and so the goods are homogeneous. In this case the equilibrium condition serves for determining the domestic production.

For the labour market, full employment is postulated. Here the equilibrium condition serves for computing the wage rate as the remaining equilibrium price.

The closure rule (as residual) could be the public budget or the balance of payments. It is also possible to implement other closure rules (for example, a fixed balance of payments and an endogenous exchange rate). Instead, the current model version uses an IS-LM type of closure. The model closure is defined by representing the way in which agents finance their deficit or allocate their surplus. The closure considers explicitly the banking sector, the allocation of private assets, the financing of the public budget and the balance of payments. It also determines interest rates of equilibrium in the financial/monetary sector. Through this closure, all prices are endogenously evaluated and there is no need for assuming an arbitrary 'numéraire'. The interest rates of equilibrium exert further feedback effects on the real sector of the model, affecting investment decisions of agents and influencing the dynamic path.

The formulation is inspired by the methodology of Bourguignon et al. [30] and Capros et al. [31].

2.7. The financial/monetary sector

The financial behaviour of economic agents is based on a portfolio model that is derived by maximizing the expected utility. The model allocates financial wealth among various assets. The allocation is made using logistic curves to ensure better simulation behaviour (for a general description see Ref. [32]). Such an approach avoids reduced-form models of financial mechanisms and uses relative interest rates as explanatory variables. Depending on whether liberalized capital markets are represented in the model, these interest rates can be derived from the equilibrium of financial supply and demand flows.

TABLE I. MATRIX OF THE FLOW OF FUNDS

	Private sector	Banks	Government	Foreign sector
Assets	Placement of assets	Supply of credits and loans		Transfer and financing of foreign debt
Liabilities	Credits and loans	Deposits	Financing of deficit	

Regarding its accounting structure, the model is based on a matrix of flow of funds (Table I), involving four financial agents, namely the private sector, Government, banks[1] and the foreign sector.

In the model the foreign and public sectors are represented only with respect to the financing of their surpluses, while the banking and private sectors are represented following an 'assets-liabilities balance' approach. However, the model fully guarantees stock-flow consistency for all transactions.

On the assets side of the private sector, total wealth is evaluated dynamically by private net savings — a variable coming from the real part of the model.

The allocation of total wealth of the private sector is described as 'risk averse investment behaviour'. Private agents are assumed to maximize the utility of the return from a portfolio. In this respect, future returns are uncertain and the risk aversion is formalized as diminishing marginal utility. The placement of assets is a function of returns and interest rate. The optimum portfolio composition involves cash, time deposits, saving deposits, Government bonds, bank bonds and treasury bills. The allocation depends mainly on the relative rates of return (assimilated to interest rates) from the above assets.

The real sector defines the demand for credit and loans. The supply of credit and loans is limited by the need to finance Government budget deficit.

Domestic borrowing of the Government is divided into two parts: the treasury bills and the Government bonds. Both can be acquired by the private sector and by commercial banks. In the private sector, investment in these two assets emanates from portfolio allocation.

2.8. Representation of the environment

The model evaluates the energy related emissions of CO_2, NO_x and SO_2 as a function of energy consumption and the abatement level per branch and per sector. The abatement level is endogenous and is linked to the production function through abatement costs that will increase the cost of using pollution intensive inputs.

The emissions are used to calculate pollutant concentrations or deposition, taking into account the transportation (between countries) and transformation mechanism of the pollutants.

In a final step, the damage generated by the concentration/deposition of pollutants is computed in physical units and valued in monetary units through a valuation function.

The model covers a wide spectrum of environmental policy instruments, including taxes, subsidies and pollution permit markets (regional and European).

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[1] The banking system as defined in this model comprises, besides the central bank, all commercial banks and specialized credit institutions.

2.9. Nomenclature/dimensions of the model

The model covers:

- 11 countries (all EU countries except Luxembourg).
- 11 products and sectors: 4 energy branches (electricity, oil, gas and coal); 3 industrial branches (energy intensive, equipment goods and consumer goods industries); agriculture, transport, market services and public services.
- 4 economic agents: households; firms; Government; ROW.
- 8 Government revenue categories: direct and indirect taxes and value added tax; subsidies, import duties and foreign sector transfers; social security and Government enterprises.
- 13 consumption expenditure categories: 9 consumption categories (food, culture, health, electricity, gas, motor fuels, other fuels, transport, housing); 3 durable goods (motor-cars, heating systems, electrical appliances); investment in dwellings.
- 2 primary production factors: labour; capital.
- 3 pollutants: CO_2, SO_2, NO_x.
- Annual time path: the model is solved annually and follows a time-forward path.
- Software: the model is solved following a combined Gauss–Seidel and Newton successive over-relaxation method by using the SOLVER/NTUA software operating in MS-Windows.

3. THE PRIMES MODEL

3.1. General presentation of the model

The energy model PRIMES (price induced model of the energy system) focuses on major areas of energy policy analysis:

- The prospects and economics of new energy supply and demand technologies;
- The energy-environment interactions and the evaluation of related policy instruments, including taxation, regulations, pollution permits, abatement technologies, energy savings and improved energy conversion technologies;
- The internal market for energy, including the consequences of third party contracting in the electricity and gas sectors, and the implications of opening up competition in the energy sector;
- The implications of the evolving international context for energy supply to the EU, including the 'energy charter' requirements.

3.2. Model characteristics

PRIMES is a partial equilibrium model for the European energy system and markets, including full coverage of their implications on the environment. The model:

— Explicitly computes the energy prices of equilibrium (i.e. it is a computable equilibrium model) and permits policy analysis of market oriented taxes, regulations and pollution permits;
— Has a flexible modular structure, allowing both for the gradual incorporation of markets and for individual and customized mathematical formulation of the demand and/or supply behaviour of agents (i.e. it is a generalized equilibrium model);
— Covers in full detail both the country specific energy systems and the overall energy market clearing at the EC level (i.e. it is a combined national and multinational equilibrium model);
— Combines an engineering oriented representation of energy supply, savings, abatement, costing and technologies with analytical economic functions for energy demand and fuel substitution; disaggregation is based on the Eurostat scheme of analytical energy balance sheets for demand, and the EFOM database for supply; multinational markets and exchanges are included for the electricity grid, the natural gas and the refinery sectors.

3.3. Main model mechanism

PRIMES is oriented towards the price driven equilibrium paradigm. The model is designed to support energy policy analysis and has the following characteristics:

— It considers explicitly and computes the formation of energy prices, enabling the study of price related and market related policy instruments; a main policy example is the carbon tax and carbon permits instruments;
— It represents market clearing mechanisms and related behaviour as the main explanatory force, enabling realistic forecasts to be made, given the increasing trend towards liberalization of markets;
— It recognizes the individual character of the behaviour of agents (for example, using different discount rates) and abolishes the central planning paradigm by modularizing the model and decentralizing optimization behaviour;
— It maintains a sufficient degree of disaggregation of sectors and technologies, and places sufficient emphasis on the interdependencies of the country-wide models to reflect internal market perspectives; the representation of market related mechanisms complies with this latter objective and includes the representation of market clearing at the Europe-wide level (for example in the gas sector).

A fundamental assumption of PRIMES is that both producers and consumers respond to changes in price. The factors determining the demand for and the supply of each fuel are analysed and represented, so they form the demand and/or supply behaviour of the agents. Through an iterative process the model determines the economic equilibrium for each fuel market. Price driven equilibrium is considered in all energy and environment markets, Europe-wide (including eastern Europe) clearing of oil and gas markets, as well as Europe-wide networks, such as the Europe-wide power grid and natural gas network.

The fundamental design feature of PRIMES is its modularity. The model is organized by an energy production subsystem for supply (oil products, natural gas, coal, electricity, others) and by end use sectors for demand (residential and commercial, transport, six industrial sectors). The individual modules vary in the depth of their structural representation. The modularity feature allows each sector to be represented in a way considered appropriate, highlighting the particular issues important for the sector, including the most expedient regional structure. The electricity module covers the whole Europe, while representing chronological load curves and dispatching at the national level. The natural gas module also expands over the whole Europe. However, coal supply, refineries and demand are represented at the national level. Furthermore, the modularity allows any single sector or group of sectors to be run independently as a debugging aid or for stand-alone analysis.

At the global level, i.e. the market clearing level, the formulation of the model corresponds to a market equilibrium of the type:

Demand = function (price)

Supply = demand

Price = inverse function (supply)

Supply side: | min $c \cdot x$
| subject to x in the set X
| $Ax = q$

Demand side: $q = Q(p)$

Cost evaluation: $u = f$ (c, x and other factors)

Equilibrium condition: $p = u + \text{taxes}$

The behaviour on the supply side, corresponding to cost minimization, is formulated as a set of linear programming models, and the behaviour on the demand side has the form of a system of (non-linear) equations; hence the equilibrium model can be written:

Solve for x, q, p, u,

where x and q denote supply and demand quantities, while u and p stand for producer and consumer prices.

The supply side may include more than one mathematical programming problem corresponding to the behaviour of several supplying agents (for example, one for refineries, one for gas and one for electricity). In addition, the possibility that some suppliers of energy commodities may also be demanders for other energy commodities (for example, the electricity sector) is included.

To solve the individual sub-models, PRIMES follows standard techniques, as appropriate to the mathematical form of each sub-model (mostly linear programming). To solve at the global level, an iteration process must be followed:

- One starts from an initial guess of the vector of energy prices;
- Then demand quantities are computed from the demand sub-models;
- Mathematical programming models for supplying agents are then solved to meet the computed demand;
- On the basis of the results of the supply sub-models, the cost evaluation equations compute producer prices which, augmented with taxes, are used to evaluate new consumer prices;
- The new consumer prices are compared with the prices used in the previous iteration and, if they are found to be close enough, the process is terminated; otherwise the process restarts by recomputing demand.

This is a Gauss-Seidel type of iteration.

The supply modules simulate both the operating and the capacity expansion activities. Thus, the model fully integrates a static solution and a dynamic solution. Dynamics are based on a backward looking anticipation mechanism (more formally, the model uses adaptive expectations).

Also, the model fully integrates the national energy system in the multinational energy system (for gas and electricity). Demand is evaluated at a national level. Electricity dispatching and capacity expansion are determined at a national level, depending, however, on a complex market allocation mechanism, operating through the electricity grid, Europe-wide. The natural gas distribution market clears at a multinational level that is even wider than the EU. The refinery sector operates at a national level, but capacities, market shares and prices depend heavily on Europe-wide competition. Coal and lignite supply curves have, on the other hand, a nation specific character. Finally, energy savings, technology progress in power generation, abatement technologies and renewables are determined for each country specific energy system.

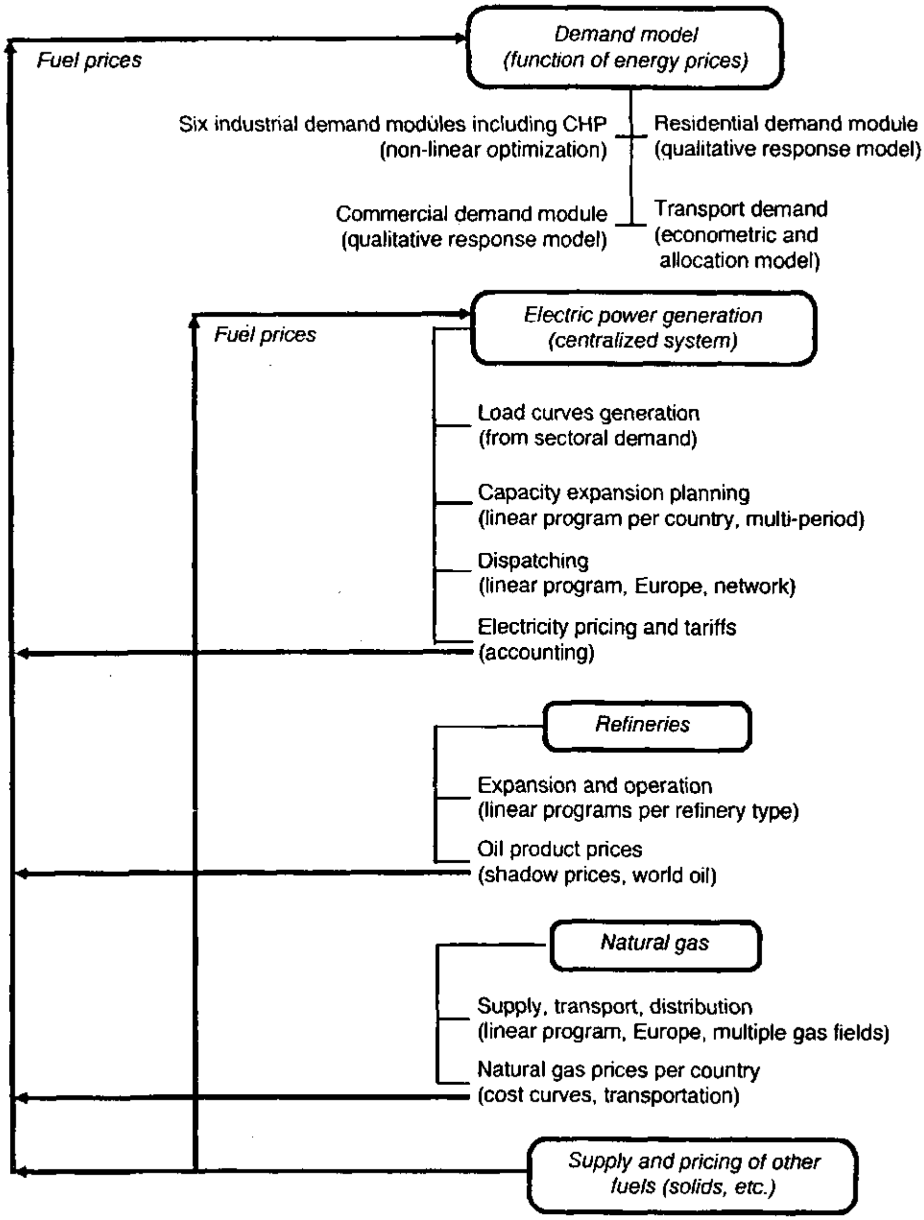

FIG. 7. Schematic of the general model.

Cost evaluation modules and price setting mechanisms are at the core of the model. The former are attached to each energy supply module and consider variable costs, fixed costs, investment costs and production efficiency, which enter either an average costing system or a marginal costing system (depending on the sector). The price setting mechanism reflects the design considerations for the market clearing regimes. Generally, four elements are considered: the supply costs, the worldwide leading prices (e.g. oil), the rental prices (for depletable fuels) and the competitors' prices (in some kind of competition). Given the modularity feature, the model formulates each market clearing regime as appropriate and, in some cases, it formulates alternative regimes to analyse the structural features of the markets. The latter is a way to study internal market issues.

3.4. Schematic of the general model

The schematic of the general model is illustrated in Fig. 7.

3.5. Technologies and environment

Particular emphasis is placed on the representation of energy technologies and their development. Technology is considered explicitly in all demand and supply sub-models and integrated in the economic behaviour of agents. Technologies for abatement of pollution from energy activities are also included. Technological development is formulated through exogenous assumptions as well as through market penetration logistic curves and learning-by-doing mechanisms.

The representation of atmospheric pollution and abatement is fully integrated in the model:

— Policy instruments include taxes, standards and pollution permits;
— Regarding the economic behaviour of each supplier or consumer, the environmental costs and constraints are considered simultaneously with energy decisions;
— Abatement technologies and stock–flow relationships are included in the sub-models;
— Emissions of CO_2, SO_2, NO_x and their concentration levels are also evaluated.

3.6. Model nomenclature

The model is dynamic, solved by five-year intervals, and follows a time-forward path.

The simulations of the PRIMES model are performed using GAMS (general algebraic modelling system) and the SIGMA/NTUA modelling software. All sub-

TABLE II. NOMENCLATURE OF PRIMES

Regions	12 EU countries
Residential demand	4 energy uses, types of households, 2 technology vintages, electric appliances
Commercial demand	2 energy uses, 2 technology vintages
Industry demand (6 models)	Iron and steel, non-ferrous, chemicals, building materials, paper, other industries; 4 energy uses, 2 technology vintages, equipment categories, abatement equipment
Transport demand	4 transport modes, 3 energy uses
Electricity production	50 thermal generation technologies, of which 10 new fossil fuel technologies, all renewables, chronological load curves, interconnections, special dispatching of renewables and combined heat and power
Refineries	4 regions with typical refinery structure, 6 typical refining units (cracking, reforming, etc.)
Natural gas	Regional supply details (Europe, Russia, Middle East, Africa, North Sea, etc.)
Fuel types	18 energy types in total
Markets	Country specific markets, cleared European level markets: refining, gas, electricity exchanges; world oil market: exogenous
Technology in demand models	Technology vintage approach, old and new, logistic functions; in industry: equipment types, e.g. boilers, furnaces, etc., abatement technologies by type of use
Power generation	Detailed treatment of new fossil fuel technologies: gas turbine combined cycle, integrated gasification coal combustion, pressurized fluidized bed combustion, atmospheric fluidized bed combustion, fuel cells, etc. Consideration of dispatching constraints for the assessment of technologies and their prospects Full representation of abatement technologies for SO_2 and NO_x, and implications of price related environmental policy instruments

models of PRIMES are written in GAMS language and require a GAMS solver. The handling of data, the global level convergence (markets) and the interactions between the sub-models are performed by SIGMA/NTUA Version 1.3, which also supports scenario simulation and reporting, all operating within the MS WINDOWS environment.

The general nomenclature of PRIMES is presented in Table II.

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ACHIEVEMENTS AND RESULTS OF THE ExternE PROJECT

N.J. EYRE
Eyre Energy Environment,
Kirkby Lonsdale,
Carnforth, Lancashire

J.E. BERRY
ETSU,
Harwell, Didcot, Oxfordshire

United Kingdom

Abstract

ACHIEVEMENTS AND RESULTS OF THE ExternE PROJECT.

The ExternE project is the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a range of different fuel cycles. It is a major project supported by the JOULE Programme of the European Commission DG XII and involves over 30 multidisciplinary teams from Member States of the European Union. The principal objectives of the ExternE project when it was launched in 1991 were: to develop a unified methodology for quantifying externalities associated with the production and consumption of energy; to use this methodology to evaluate the external costs of different fuel cycles at sites throughout Europe, and to identify critical methodological issues and research needs. To date, good progress has been made on all these aspects. The paper summarizes the achievements and results of the project. A major result of this work is the 'bottom-up' methodology that has been developed. It provides a transparent basis on which different impacts, technologies and locations may be compared, and it is suitable for the evaluation of health and environmental damages due to incremental increases in electricity production. This methodology has been successfully used to assess the externalities of a range of fuel cycles. Results are presented for seven fuel cycles, namely the coal, lignite, oil, gas, nuclear, wind and hydro fuel cycles. In each case the priority impacts are discussed together with the important issues that have been raised in the course of the work.

1. INTRODUCTION

Fuel cycle externalities are the costs imposed on society and the environment that are not accounted for by the producers and consumers of energy; in other words, they are damages which are not reflected in the market price. They include physical damage to the natural and built environment, as well as impacts on recreation, amenity, aesthetics and other contributors to individual utility. Traditional economic assessment of fuel cycles has tended to ignore these effects.

Concern over widespread degradation of the environment caused by emissions from the major fuel cycles for electricity generation has mounted since the early 1970s. The impacts of acid deposition and ozone have been studied extensively. More recently, the accumulation of greenhouse gases in the atmosphere and the consequential changes to the Earth's climate have caused even more concern. At the same time, the potential environmental and social problems of nuclear power have been discussed increasingly. Electricity generation based on renewable energy sources is usually considered to be more environmentally benign, though even these technologies are not impact free.

Although the theoretical basis for including external costs in economic analyses is well understood in neoclassical economics, an acceptable methodology for their calculation has not been established. The studies of Hohmeyer [1], Ottinger et al. [2] and Pearce et al. [3] are well known examples of attempts to calculate the environmental externalities of electricity use. However, they are of a somewhat preliminary nature. The task of quantifying externalities is rendered difficult by a range of problems, including:

- dependence on technology,
- dependence on location,
- uncertainties in the causes and nature of impacts on health and the environment,
- lack of suitable economic valuation studies, and
- methodological questions involving the use of environmental and economic results for this application.

In consequence of this, the Directorate General XII (DG XII) of the European Commission established a collaborative research programme with the United States Department of Energy to identify an appropriate methodology for this type of work. Following this collaboration, the DG XII programme has continued as an independent project within the Joule programme — known as the ExternE project.

The ExternE project has the following principal objectives:

- to develop a unified methodology for quantifying the environmental impacts and social costs associated with the production and consumption of energy from different fuels;
- to use this methodology to evaluate the external costs of incremental use of different fuel cycles in different locations in the European Union (EU);
- to identify critical methodological issues and research needs.

In the present phase of the study, the following fuel cycles for electricity generation have been assessed: coal, nuclear, lignite, oil, gas, wind, photovoltaics, solar/thermal electric, various biomass resources and hydropower, as well as technologies for energy conservation. A series of reports describing the methodology used and its application to the individual fuel cycles is being published (see Refs

[4–9]). Further work is being done to implement the fuel cycles in different European locations and to extend the methodology to include non-environmental externalities, such as energy security.

This paper presents a summary of the project's achievements and results to date. The work has been reviewed extensively through the use of expert networks within the project and by comparison of the work of different teams. A detail description of the methodology and the assessments undertaken is beyond the scope of this paper. The interested reader should consult the series of ExternE reports.

2. BASIC METHODOLOGY

External costs may be estimated by damage assessment (our approach) or by consideration of abatement costs implicit in regulation. The latter approach measures a 'regulatory revealed preference', which will be related to damage costs if the regulatory process is based on a cost–benefit analysis. However, this approach does not dispense with the need to measure damage costs at some time as an input to the analysis. Damage costs have been the principal concern of the ExternE project.

In the assessment of damages, two broad methodological approaches are used. They are usually described as 'top-down' and bottom-up' methodologies. Top-down analyses use highly aggregated data, for example national emission and impact data, to estimate the damage costs of particular pollutants. This methodology predominates in earlier published studies. It has relatively low data needs and may give reasonable estimates for average damage costs. However, care is required to ensure that poor science and/or economics is not implicit in the assessments used. Most importantly, this approach does not easily allow for consideration of variation in impacts due to location or time.

In contrast, the bottom-up methodology (also known as the damage function or impact pathway approach) uses technology-specific emission data for individual locations. These data are used together with pollutant dispersion models, detailed information on the distribution of receptors and thoroughly reviewed dose response functions to calculate the physical impacts of the specified emissions. The final stage in the analysis is monetary valuation. The methodology for this comes from welfare economics, where value is equated with willingness to pay for improved environmental quality or willingness to accept environmental damage. This bottom-up approach overcomes many of the weaknesses of the top-down approach. Full details of the methodological approach are given in Refs [4–9].

3. FOSSIL FUEL CYCLES

The bottom-up methodology has been implemented for a variety of fossil fuel fired cycles at realistic locations in Europe:

— Two new coal fired electricity generating fuel cycles, at West Burton in Nottinghamshire (United Kingdom) and Lauffen in Baden-Württemberg (Germany);
— A lignite fired fuel cycle near Grevenbroich in Rheinland (Germany);
— Two different oil fuel cycles at Lauffen;
— A natural gas power station at West Burton.

The power generation technologies are typical of the choices of the relevant fuels in the EU in 1990. The pulverized coal and lignite fired plants use steam turbines. The oil fired options are a gas turbine plant using light oil, designed for peak load operation, and a new combined cycle plant, designed to use heavy oil. The locations are also reasonably typical for new fuel cycles, and European fuel sources are used in each case. The emissions satisfy the requirements for new plant under the Large Combustion Plant Directive of the EU. Emission factors are characteristic of the fuel types, so that there are significant variations between fuels, especially in emissions of particulates and sulphur dioxide.

The impacts have been analysed by receptor type, distinguishing human health (public and occupational), human amenity, crops, forests, terrestrial ecosystems, fisheries and building materials. The only exception is the impact of global warming. The impacts of climate change are extremely diverse, complex and interrelated. The ExternE reports review the state of the art in this field and conclude that, with the current state of knowledge, it is not possible to make any reliable estimates of global warming damages [5].

Table I summarizes the results obtained for the fossil fuel cycles. The salient features of the analysis are presented in the following subsections. Many impacts, including some which are potentially important, cannot be monetarized. Therefore, a full aggregation, to provide a value for the 'total environmental externality', cannot be achieved. In addition, the levels of uncertainty are quite high, especially for the potentially large damages. However, the relative results for the different fuel cycles depend largely on emission rates and therefore are fairly robust.

3.1. Public health impacts

The priority pathways for public health effects are associated with air pollution, with the power plant being the most important source. The dominant health impacts identified in this assessment are acute effects on mortality due to particulates (including acid aerosols). However, it must be noted that there is a high level of uncertainty in the damage estimates, reflecting uncertainty in both the epidemiology

TABLE I. DAMAGE ESTIMATES FROM THE ExternE PROJECT FOR THE MAIN FOSSIL FUEL CYCLES

Damage category	Valuation estimate (mECU/kW·h)					
	Coal		Lignite	Oil		Gas
	UK	Germany	Germany	GT	CCGT	UK
Global warming	NQ	NQ	NQ	NQ	NQ	NQ
Public health	4[a]	13	10	11	10	0.5[a]
Occupational health: diseases	0.1	0.3	Neg.	Neg.	Neg.	Neg.
Occupational health: accidents	0.8	2.0	0.1	0.5	0.3	0.1
Agriculture	0.03	0.02	0.02	0.04	0.02	NQ
Timber	0.004	0.009	0.004	0.013	0.009	Neg.
Terrestrial ecosystems	NQ	NQ	NQ	NQ	NQ	NQ
Marine ecosystems	NQ	NQ	NQ	0.2	0.2	0.001
Fisheries	IQ	NQ	NQ	NQ	NQ	NQ
Materials	0.8	0.2	0.1	0.3	0.2	0.06
Noise	0.2	NQ	NQ	NQ	NQ	0.03
Other impacts	NQ	NQ	NQ	NQ	NQ	NQ
Sub-total	6[a]	16	10	12	11	0.7[a]
Total	NQ	NQ	NQ	NQ	NQ	NQ

NQ — not quantified in this project, though some discussion of effects is given.
IQ — impacts have been quantified but not yet valued.
Neg. — negligible.

[a] Public health impact assessed over the UK only.

data and the valuation methodologies used. In particular, two important assumptions have been made: first that there is no threshold for particulates below which health is not affected, and second that the full value of a statistical life is applicable to all deaths, no matter how short the period of life that is lost or how poor its quality. A different view of these assumptions would lead to much smaller damage estimates.

The large differences between the results for the UK and Germany are due to differences in the geographical limit of the analysis. The German analysis has been undertaken on a European scale, while the analysis for the UK power stations has been restricted to the UK. Therefore, the results are not directly comparable. The important pollutants all have ranges of hundreds of kilometres and therefore the results from the German implementations are more comprehensive. Confining the analysis to the local area of a power plant (typical practice in environmental impact assessment) can easily underestimate the aggregate impact by an order of magnitude or more.

3.2. Occupational health impacts

Occupational risks result from air pollution and accidents. Within the coal fuel cycle, coal miners are particularly affected by air pollution due to radon and dust. The effects of the former can be estimated from standard assessments of radiological health impacts. Damages in the UK are lower in each case, largely because of greater productivity in UK underground mines. The impacts of the lignite fuel cycle are smaller because open cast extraction was considered. No detailed evaluation was made of occupational diseases associated with the oil and gas industries in the North Sea because the required data were not available.

Health impacts from accidents were estimated using national data from the UK and Germany. Accidents occur at all stages of the fuel cycle and analysis of the full fuel cycle is therefore important. Fuel extraction and transport, and construction, operation and decommissioning of the power plant have all been evaluated for each fuel cycle.

3.3. Effects of atmospheric pollution on crops

The most important impacts of atmospheric pollution on crops are due to ozone, followed by sulphur dioxide. Contributions from the deposition of acid and nitrogen are largely masked by additions of fertilizer and lime in normal agricultural practice, and are less important. Recent evidence indicates that there may be significant synergistic effects and indirect effects, for example via impacts on pests.

ExternE provides the first bottom-up assessment of the impacts of individual power stations on aggregate crop yields. The values presented in Table I reflect for the UK the impacts of SO_2 on cereal crops and for Germany the impacts of SO_2 on cereal crops and of ozone on wheat. The dose response functions used have been thoroughly reviewed and therefore represent a significant improvement compared with other published work.

3.4. Forests

A number of models are available that indicate major forest damage in areas where critical loads and levels are exceeded. However, these models have not been widely accepted; indeed, some have been heavily criticized. Hence, the ExternE project has not used these models, instead preferring to use simple dose response functions derived from experimental and survey data. The results obtained indicate modest losses of timber production in areas where critical loads are exceeded. These areas have been reduced considerably by sulphur emission abatement measures in recent years and in general they are far from the power plants considered. At the present time the methodology that we have used seems likely to underestimate damages, possibly significantly. It is presented here as the method of choice, partly because of a lack of faith in alternative models, and partly, by demonstrating that significant exposure response relationships can be derived from existing information, to encourage reassessment of the wealth of available data. It should also be noted that the impact of older power stations without sulphur abatement would be several times larger.

Forests play many important roles; wood production and recreational sites have been the most widely considered by economists. However, other functions, such as soil stabilization, carbon retention and protection of biodiversity, are at least as important. Our monetary valuations of forest damage are therefore only partial, which is a further reason for believing that the full cost will be significantly higher than that suggested by our analysis.

3.5. Other ecosystems

A range of emissions into air from all fossil fuel cycles have impacts on unmanaged terrestrial ecosystems. Acid deposition depletes base cation concentrations in soils and mobilizes aluminium; nitrogen deposition has a fertilizing effect and affects inter-species competition; ozone causes cell damage. Impacts of these regional scale pollutants have been identified in the field. They are rather long term impacts and therefore may be difficult to distinguish from effects of other stresses. Concerns about these impacts focus on loss of habitats and 'biodiversity'. The complexity and diversity of ecosystems prevents the description of impacts in terms of dose response functions. Instead, attention has concentrated on the thresholds for effects — critical loads and levels. These are the principal scientific tools in policy analysis in this field.

Our study has made a multidisciplinary review of the issues involved in damages to unmanaged ecosystems. The problems identified are very considerable, and the work has clarified rather than solved them. It is concluded that monetary valuation of ecosystems is not a credible approach at the present time. One exception is the oil fuel cycle, where impacts on marine and coastal ecosystems due to emissions of crude oil have been estimated on the basis of the costs associated with cleanup exercises.

3.6. Acid deposition: damage to fisheries

Major reductions in fish populations in some areas have been documented in several European countries and these have been linked with acid deposition. The assessment of damage to freshwater fisheries represents a significant advance in the state of the art. For the first time, validated models and dose response functions have been used to estimate fish loss over an extended time period. A method for valuation of freshwater systems has been identified but not applied because of insufficient data.

3.7. Building materials

Pollution damage to materials is qualitatively well documented and acid species are the main causes. Materials are used for many purposes, but our analysis is largely confined to components of buildings, and to that extent the results underestimate the total damage. Account has, however, been taken of the effects on galvanized steel used in the agriculture, transport and power sectors. In addition, the analysis is confined to the costs of repair and maintenance of utilitarian buildings, with no allowance for aesthetic effects or damage to historic buildings and cultural monuments.

The dose response functions for acid attack are derived from an expert assessment of the relevant literature. They consider only uniform corrosion over the whole surface, which is often, but not always, the dominant damage mechanism. The rates of corrosion are converted to a repair or replacement frequency, using expert judgement, and the repair is valued using market prices.

The results indicate that corrosion damage is a small, but significant, impact. The impacts are caused mainly by acid emissions; the impacts of soiling by particulates are much smaller. The damages therefore vary considerably by fuel type. The identified differences between British and German power stations arise largely from variation in the materials inventory for each country and from differing views on the extent to which materials are exposed to pollution. These issues require further investigation.

3.8. Noise

Noise can affect both human health and amenity. However, hearing damage only occurs at high noise levels to which only workers seem likely to be exposed, but this should be avoided by the use of ear protection. Our analysis therefore concentrates on amenity loss to the general public from fuel cycle noise. The noisiest stages of the fuel cycle occur at the power station and in transport by road and rail, for which good noise emission data are available.

3.9. Global warming

The greenhouse gas emissions from each fuel cycle are known accurately. They are dominated by carbon dioxide emissions, mainly from power stations. A modelling procedure used by the Intergovernmental Panel on Climate Change (IPCC) has been applied to estimate the temperature rise. The impacts of global warming are predicted to affect a huge range of receptors. Since damages depend on the scenario considered and are long lasting, their estimation is complex and the results are very uncertain. Damages are potentially very large. Estimation of the impacts is rendered difficult by poor understanding of the likely regional variation in climatic change. Quantification is therefore difficult.

The most comprehensive assessments of the impacts, for example by the IPCC, are largely qualitative. In ExternE, to date, there is no independent analysis — only a review of the literature. However, it is clear that global warming has potentially serious implications for agriculture, forests, natural ecosystems, sea level and water supply.

It is concluded that global warming impacts may well be the most serious effects of the fossil fuel cycles, with potentially serious implications for sustainable development. However, the impacts cannot be calculated with any accuracy. Estimation of damages requires scenario definition and ethical judgements, which it is misleading to present as the results of a technical and objective exercise.

3.10. Other impacts

The impacts identified above do not represent a complete list of the external environmental effects of the fossil fuel cycles. Other impacts include:

- Effects of pollutants from solid mine waste on water quality;
- Impacts on buildings and infrastructure due to coal mining subsidence;
- Impacts of solid waste from power stations;
- Impacts of emissions of radionuclides and of ^{14}C dilution;
- Visual amenity impacts of structures;
- Reduced visibility due to pollution;
- Increased traffic congestion;
- Impacts of emissions from power stations to water;
- Impacts of trace metal emissions;
- Water use.

In most cases these impacts, which are due to fossil fuel cycles using modern technology, are expected to be very small when expressed in mECU/kW·h.

4. NUCLEAR FUEL CYCLE

A similar methodology has been implemented for the nuclear fuel cycle. The fuel cycle studied is typical of current European practice, involving the use of enriched uranium fuel in a pressurized water reactor (PWR) with fuel reprocessing. All stages of the fuel cycle are in France.

The uranium is mined and milled at Lodève, before conversion to uranium tetrafluoride at Malvesi, both in the south of the country. The power station is a 900 MW PWR at Tricastin in the Rhône valley, supplied with fuel from the nearby Pierrelatte enrichment plant. Reprocessing is done using the PUREX process in the new UP3 facility at the La Hague plant on the north coast. Radioactive solid wastes are disposed of in engineered facilities — low level waste (LLW) and intermediate level waste (ILW) at the Centre de l'Aube in eastern France, and vitrified high level waste (HLW) at a hypothetical site in the Massif Central.

These choices are characteristic of the incremental nuclear capacity in France in the 1990s. Particularly at the reprocessing stage, they are not typical, technically or environmentally, of earlier plants. In contrast to the fossil fuel cycles, the power generation stage in the nuclear fuel cycle is not the dominant source of emissions.

The analysis of the nuclear fuel cycle focuses very largely on the radiological human health effects that result from exposure to radioactivity, considering both public and occupational health impacts. This should not be interpreted as meaning that there are no impacts on ecosystems. However, these are not considered to be priority impacts for normal operation.

The analysis of impacts of releases from accidents involves additional, complex issues, which have been extensively considered in the ExternE project and in parallel US work [10, 11], but which have not yet been resolved satisfactorily and therefore are not included here. Similarly, the impacts of HLW disposal beyond 100 000 years are not included here. Malicious use of nuclear materials and deliberate damage to nuclear facilities, whether by nations or individuals, are also difficult to assess. They are excluded from the ExternE analysis, although they clearly represent a major issue for the nuclear fuel cycle.

For some of the impacts, effects may be experienced over a wide range of spatial scales and time-scales, and these differences affect both the level of uncertainty in the analysis and public perceptions of the issues. For clarity, the impacts are therefore classified as local, regional or global in scale, and as short term (within 1 year), medium term (1 year to 100 years) or long term (100 to 100 000 years).

Although a comprehensive study of physical impacts has been completed, it must be stressed that the final result should only be considered as a sub-total; it has not been possible to include the assessment of all possible impacts that should be included in a final total value. It is also important to stress that there has been very limited determination of the extent to which these impacts are to be considered externalities.

Table II presents a summary of the undiscounted costs of the physical impacts estimated for all stages of the nuclear fuel cycle under *normal* operation. The public health impacts are reported for local, regional and global population categories and for three time periods. The occupational impacts are included in the short term category; they are due essentially to non-radiological accident injuries. The radiological impacts occur in the medium and long terms.

The assessments of the priority impacts for all stages of the nuclear fuel cycle have been completed. Without a discount rate, the public health costs on the local, regional and global scales contribute 94% of the 2.5 mECU/kW·h sub-total, the remaining 6% being occupational impacts. A key factor in the interpretation of these results is the dimensions of time and space. These boundaries can have a profound effect on the final result. The expected time of occurrence of an impact becomes very important if any discount rate is applied, as does the decision as to whether or not to include potential global impacts. The global impacts contribute 91% of the total cost of the fuel cycle.

The releases from the electricity generation stage contribute about 14%, but the global impacts, predominantly due to the long lived ^{14}C releases, dominate the final result. The reprocessing stage of the nuclear fuel cycle is the largest contributor, at 2 mECU/kW·h. It must be stressed that, even though this value is large compared with the rest of the values, it is due to very small doses that are summed over 100 000 years and an assumed constant world population of 10 000 million people. The actual radiation dose that an individual person will receive is insignificant compared with the natural background doses. The usefulness of the monetary valuation of these types of impacts must be considered carefully before the values are used for decision making.

On the local and regional scales, the atmospheric and liquid releases are equally important. Most of the impacts result from atmospheric releases at the mining and milling stages, whereas the largest liquid releases are from HLW disposal. When a discount rate is applied, the HLW costs are reduced to zero, so the impacts are mainly due to atmospheric releases.

The use of a discount rate reduces the external costs of the fuel cycle and changes the relative importance of the different impacts. The sub-totals of the costs presented for all stages of the nuclear fuel cycle are about 0.1 mECU/kW·h and 0.05 mECU/kW·h, respectively, for discount rates of 3% and 10%. The cost contribution from the reprocessing stage changes from 77% at a zero discount rate to 15% at a 3% rate and to 4% at a 10% rate. This is due to the fact that the largest portions of the impacts are long term impacts and therefore are greatly reduced by discounting.

When a discount rate of 3% is applied, the most important contributor becomes the costs from the impacts of the construction of the reactor (35%) because discounting does not reduce these very short term impacts. The next most important contributors are the operation phase of electricity generation and mining and milling

TABLE II. SUMMARY OF CALCULATED DAMAGE COSTS (mECU/kW·h) AT 0% DISCOUNT RATE BY SPACE AND TIME FOR THE NUCLEAR FUEL CYCLE IN FRANCE, EXCLUDING ACCIDENTS

Range	Time-scale					
	Short		Medium		Long	
Local	Mining	1×10^{-2}	Mining	3×10^{-2}	Mining	3×10^{-4}
	Conversion	6×10^{-4}	Conversion	3×10^{-4}	Conversion	4×10^{-6}
	Enrichment	1×10^{-3}	Enrichment	1×10^{-6}	Enrichment	4×10^{-6}
	Fabrication	8×10^{-4}	Fabrication	1×10^{-3}	Fabrication	6×10^{-8}
	Construction	3×10^{-2}	Construction	0	Construction	0
	Generation	1×10^{-2}	Generation	5×10^{-2}	Generation	1×10^{-8}
	Decommissioning	0	Decommissioning	2×10^{-2}	Decommissioning	0
	Reprocessing	3×10^{-3}	Reprocessing	3×10^{-4}	Reprocessing	3×10^{-6}
	LLW disposal	0	LLW disposal	2×10^{-5}	LLW disposal	2×10^{-6}
	HLW disposal	0	HLW disposal	9×10^{-8}	HLW disposal	3×10^{-2}
	Transportation	4×10^{-4}	Transportation	4×10^{-4}	Transportation	0
	Sub-total	7×10^{-2}	Sub-total	1×10^{-1}	Sub-total	3×10^{-2}
Regional	Mining	0	Mining	2×10^{-2}	Mining	2×10^{-4}
	Conversion	0	Conversion	3×10^{-7}	Conversion	2×10^{-6}
	Enrichment	0	Enrichment	1×10^{-7}	Enrichment	7×10^{-7}
	Fabrication	0	Fabrication	2×10^{-6}	Fabrication	1×10^{-8}

Regional	Construction	0	Construction	0	Construction	0
	Generation	0	Generation	3×10^{-3}	Generation	2×10^{-9}
	Decommissioning	0	Decommissioning	0	Decommissioning	0
	Reprocessing	0	Reprocessing	1×10^{-2}	Reprocessing	2×10^{-3}
	LLW disposal	0	LLW disposal	0	LLW disposal	0
	HLW disposal	0	HLW disposal	0	HLW disposal	0
	Transportation	0	Transportation	0	Transportation	0
	Sub-total	0	Sub-total	3×10^{-2}	Sub-total	2×10^{-3}
Global	Mining	0	Mining	2×10^{-5}	Mining	0
	Conversion	0	Conversion	2×10^{-7}	Conversion	0
	Enrichment	0	Enrichment	7×10^{-8}	Enrichment	0
	Fabrication	0	Fabrication	1×10^{-9}	Fabrication	0
	Construction	0	Construction	0	Construction	0
	Generation	0	Generation	3×10^{-2}	Generation	3×10^{-1}
	Decommissioning	0	Decommissioning	0	Decommissioning	0
	Reprocessing	0	Reprocessing	2×10^{-1}	Reprocessing	2
	LLW disposal	0	LLW disposal	1×10^{-4}	LLW disposal	5×10^{-3}
	HLW disposal	0	HLW disposal	0	HLW disposal	0[a]
	Transportation	0	Transportation	0	Transportation	0
	Sub-total	0	Sub-total	2×10^{-1}	Sub-total	2

[a] Without intrusion, there is no expected impact over the 100 000 year period evaluated.

(21% and 19%, respectively). These do not show as drastic a decrease because of the importance of the short term occupational health impacts.

For the higher discount rate of 10%, the cost from the construction of the reactor rises to 68% of the sub-total, followed by mining and milling (13%) and operation of the reactor for electricity generation (12%). The most dramatic drop in cost can be seen for the waste disposal operations where the values become essentially zero. Clearly this is due to the fact that the impacts from waste disposal will mostly occur in the future.

As discussed previously for the fossil fuel cycles, the uncertainty associated with the results may be significant. It arises from uncertainties in the models used and in the input data, and from the lack of information for some pathways. As a general rule, the longer the time span and/or the larger the region considered in the model, the larger the uncertainty.

5. RENEWABLE ENERGY SOURCES

A wide range of renewable energy sources can be used for power generation. The results presented here are from two examples: hydropower, which is the only significant, long established technology for power generation; and wind, which is the most advanced of the new renewable sources.

Wind farms are studied at two locations in the UK. The first is a rather small wind farm — the first commercial project in the UK — in an agricultural setting at Delabole in south-west England; the second is a very large project (more than 100 turbines) on open moorland at Penrhyddlan and Llidiartywaun in central Wales. They are probably reasonably representative of high wind speed locations in coastal and upland areas of north-west Europe.

The hydropower implementations consider two very different projects. The first is a new, major (500 MW) extension to an existing large hydropower system at Sauda in south-west Norway. It involves increased production at two existing reservoirs (by increasing the inundated area by 2.6 km^2) and six new diversion projects. The average electricity production will increase by 1.3 TW·h annually (from 1 TW·h currently). The second project is an existing system on the La Creuse river in central France. It is a smaller (20 MW) project, involving three 19 m high dams, creating lakes with a total area of 1.1 km^2 in the river gorge. Numerical evaluation of damages at this site is incomplete.

The major impacts of these fuel cycles, at least at these locations, are on human amenity — noise and visual effects and impacts on recreation. In the Norwegian hydropower study, the damages at the particular site were assessed by a contingent valuation method (CVM) study; the French hydropower study is undertaking a travel cost method evaluation. These approaches allow highly site specific effects to be captured, but make the results difficult to generalize. In contrast, for the wind fuel

TABLE III. EXTERNAL COSTS OF RENEWABLE ENERGY FUEL CYCLES: DAMAGE ESTIMATES FOR WIND TURBINES AND HYDROPOWER

Damage category	Fuel cycle damages (mECU/kW·h)			
	Wind turbines		Hydropower	
	Delabole, UK	Penrhyddlan, UK	Sauda, Norway	La Creuse, France
Noise	1	0.07	Neg.	Neg.
Visual amenity	NQ	NQ	2[a]	NQ[b]
Impacts of acid emissions	8% of coal fuel cycle		NQ[c]	NQ[c]
Global warming	1% of coal fuel cycle		NQ[c]	NQ[c]
Public accidents	0.09	0.09	NQ	NQ
Occupational accidents	0.3	0.3	>0.003	0.05
Ecosystem impacts	Neg.	Neg.	2[a]	NQ[b]
Direct agricultural impacts	Neg.	Neg.	0.01	Neg.
Direct forestry impacts	0	0	0.0003	Neg.
Impacts on water supply	0	0	0.008	Neg.
Recreational impacts	NQ	NQ	2[a]	NQ[b]
Sub-total	2	1	2	NQ
Other impacts	NQ	NQ	NQ	NQ
Total	NQ	NQ	NQ	NQ

[a] This value is the result of a CVM study valuing the ecosystems, cultural sites and recreational and aesthetic impacts.

[b] Results from a valuation study using the travel cost method are not yet available.

[c] These are the impacts of secondary emissions. Comparable damages are not included for the fossil and nuclear fuel cycles.

NQ — not quantified.

Neg. — negligible damage.

cycles, damage assessment has been undertaken by transferring results from other locations. This produces less reliable results for the site but makes generalization easier.

External costs of emissions necessarily concentrate on the emissions from manufacturing and constructing renewable energy facilities. As expected, these emissions are a small fraction of those from the operation of fossil fuel power stations. Similar assessments were not undertaken for the fossil and nuclear fuel cycles, because it is clear that the external costs of these secondary emissions will be small compared with those of direct emissions.

The results are summarized in Table III; full details are presented in an ExternE report [9].

6. CONCLUSIONS

A major result of this work is the methodology that has been developed. This is a significant advancement compared with earlier studies on external costs of energy. It provides a transparent basis on which different impacts, technologies and locations may be compared. It is suitable for evaluation of the health and environmental damages due to increments in electricity production, with or without monetary valuation of the impacts.

The estimates of damage are based on a thorough review of scientific and economic studies. This does not mean that exact values have been established for external costs. Indeed, one of our most important conclusions is that the uncertainties are large. Previous analyses, offering apparently precise estimates, have tended to neglect uncertainty and, in that respect, are very misleading. For many long term effects, the impacts are very scenario dependent. Our knowledge of the future is too uncertain to allow reliable estimates of damages to be made in these cases. Damage estimates are strongly dependent on time effects — both the real value of environmental benefits over time and the discount rate. We conclude that improved methods are required for presenting the uncertainty inherent in this field.

The fossil, nuclear and renewables fuel cycles differ in important ways. Many of the more problematic social and environmental impacts are difficult to quantify, and therefore direct comparison of the fuel cycles is difficult. For these reasons, the results in Tables I–III need to be interpreted with extreme care. The total damages are not calculated for any fuel cycle.

The damages assessed cover a very wide range of spatial scales and time-scales. In general, the impacts over the largest ranges and the longest time-scales are potentially the largest, but they are also the most uncertain, for example global warming impacts and, in the nuclear fuel cycle, impacts due to ^{14}C. These areas require the most further research, both to reduce the uncertainties and to develop appropriate tools to inform policy makers and the general public.

For renewable projects the dominant direct impacts are local in character and therefore inevitably site specific. However, the results for the wind fuel cycles show that the indirect impacts arising during the manufacture of the turbines are important and in one case are the dominant impacts. More studies are required to enable an understanding of the way in which site parameters influence impacts, but it is already clear that good planning of site location is the key issue. It is therefore concluded that, if sites are sensitively located, the environmental external costs of renewable electricity generation are smaller than those of 'conventional' electricity generation.

Model development will allow some improvements in quantification. However, in some cases (notably nuclear accidents, ecosystem and global warming impacts), reliable monetary valuations are not a realistic short term objective. This conclusion has significance for policy making. Monetary valuation of impacts is an important tool, but other tools for comparing impacts are still needed. A large number of research requirements have been identified and they are discussed in the full reports on each fuel cycle [6–9].

The damage estimates are valid only for the technologies considered. Most impacts depend linearly on the relevant emissions, and the emissions from different technologies vary considerably. For example, the use of cogeneration will reduce fossil fuel cycle damages per kilowatt-hour by a factor of two. Clean coal technologies might reduce coal fuel cycle externalities, except global warming impacts, to very low levels. In contrast, for the important impacts of acid emissions, damages from older power stations will be many times larger. Similarly, older nuclear installations have higher specific emissions and therefore higher damages.

Table I shows that, in the coal fuel cycle (when analytical differences are taken into account), damage estimates are similar for the UK and German plants. This is due to the reduction of local impacts by the use of high stacks and the long range nature of the most important impacts. The EU legislation has harmonized new plant emission standards, and therefore the releases from each location are broadly similar. For long range impacts, local variations in receptor density are unimportant because the damage reflects average European conditions. Damage costs for fossil fuel cycles, using similar fuel and technology, may therefore be fairly uniform across the EU. This can only be verified by similar analyses in more locations. Interestingly, for the nuclear fuel cycle, preliminary results for five additional reactor sites in France also show that for both environmental releases and occupational doses the results do not differ significantly between sites.

All the local pollution impacts considered are small. Potentially severe local impacts are the subject of many control measures in the EU Member States, which have reduced these damages significantly. This does not mean that residual local impacts are unimportant, since they may represent a serious disadvantage to a small number of people. More stringent environmental controls may therefore be justified for reasons other than economic efficiency.

The dominant damages for fossil and nuclear emissions are due to long range pollutants, and most of the aggregate damage is experienced as very small impacts over a large number of receptors. Limiting environmental assessments for these technologies to short term or local impacts is therefore wholly unjustifiable, but the current monetary valuation methodologies have some limitations when applied to these circumstances.

Because of the size of the uncertainties, it is not possible to use the damage estimates derived in this study to design 'optimum' economic instruments. However, some policy conclusions can be drawn. For example, it can be argued that the health and materials damage estimates for the coal fuel cycle evaluated in this study justify the new plant standards of the Large Combustion Plant Directive of the EU. Sustainability issues are of major concern to environmental policy makers, although such issues are as yet poorly captured by monetization. However, the impact assessments and damage estimates derived in this study provide valuable information that can be used to compare the effects of different fuel cycles on sustainability.

It is concluded that a methodology for bottom-up analysis of environmental damages has been developed and has produced valuable results. The methodology has intensive data requirements. However, our work shows that it is the only reliable approach to estimating impacts as a function of location and technology. Now that the methodology has been developed, future analysis will be easier. Advances are being made in all the disciplines on which the analysis is based, so that future studies will yield better results.

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Finally, the views expressed in this paper are those of the authors and not necessarily those of the European Commission or the UK Department of Trade and Industry.

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SOME TRANSBOUNDARY ENVIRONMENTAL ISSUES OF PUBLIC CONCERN

R. WILSON
Mallinckrodt Professor of Physics,
Harvard University,
Cambridge, Massachusetts,
United States of America

Abstract

SOME TRANSBOUNDARY ENVIRONMENTAL ISSUES OF PUBLIC CONCERN.

There are two complementary approaches to studying the environmental effects of fuel use and energy conversion. The first approach is to be completely systematic and to follow through each technology in great detail, and to itemize each impact, whether large or small. The second approach, followed here, is to pick out those items that dominate either the risk or impact or the public perception thereof, and try to understand them in some detail. The following items are discussed in the paper: (a) The probability and effect of a severe nuclear power accident. Experts believe that the probability of a severe accident in a pressurized water reactor is small, and the effect would be far less than the effect of the Chernobyl accident. But a large number of people believe otherwise. (b) The effect upon health of particulate air pollution at the present levels. More and more experts believe that particulates kill 70 000 people per year in the United States of America, but this has not yet been officially admitted by any Government. (c) The probability that increased carbon dioxide emissions from burning fossil fuels will cause a global climate change. There was intense Government attention at the meeting in Rio de Janeiro in 1992 and at the meeting in Berlin in 1995. But the estimates of the Intergovernmental Panel on Climate Change have decreased over the last five years. (d) Although there is public concern about nuclear waste, this is not justified by the calculations. The points discussed in the paper are: the reasons for this concern and the question why there is not comparable concern about coal waste. A final issue is very important, namely the effect of the technology on the outbreak of a catastrophic war, such as might be caused by proliferation of nuclear weapons among many States.

1. INTRODUCTION

At various times, environmentalists raise a large number of questions about fuel consumption and energy use. Some of these might not qualify to a professional as environmental issues. Therefore, some of them are often omitted in general discussions because they are not strictly environmental issues. But each has been called an environmental concern at various times and all are worth considering. They might be called 'environmentalist' issues, and thereby qualify for consideration. They concern impacts or effects upon:

— the visual environment,
— ecological systems,
— the world climate,
— waste problems,
— occupational health,
— occupational safety,
— public health,
— public safety,
— sabotage,
— terrorism,
— life-style,
— national independence,
— probability of war.

These issues are not always consistent, and it is useful to consider them separately. In order to maintain perspective, it is necessary to make comparisons between various fuel sources. It is important to be comprehensive, as is the case for many other studies, but it is also very important to emphasize the large effects and those that are perceived by the public to be large. I shall emphasize a few of these and note that they are all issues in which the matter of concern crosses national and even continental boundaries; in addition to stretching in space, some of these issues stretch in time.

The discussion of the total effect upon health is dominated by several items:

(a) Probability and effect of a severe nuclear power accident;
(b) Effect of particulate air pollution at the present levels;
(c) Probability that carbon dioxide emissions will cause global warming;
(d) The waste problems of fuel use.
(Why is there public concern about nuclear waste although it is not justified by the calculations? Why is there not comparable concern about coal waste?)

2. PROBABILITY AND EFFECT OF A SEVERE NUCLEAR POWER ACCIDENT

In spite of the greatest possible care, accidents will happen. It is one of the greatest triumphs of modern civilization that we have been able to reduce industrial accidents steadily over the last 150 years. An exception was the former Soviet Union, whose political system seemed to prevent the learning from mistakes that is necessary to have a safe society. For large scale uses of fuels, we store a lot of energy in one place, and often that place is where there are a lot of people. It is this which implies the potential for disaster.

The collection of accident data and the science of calculating future accident frequency have been greatly developed over the last 20 years [1, 2]. Accidents with liquefied natural gas (LNG) and oil happen once a year worldwide. In some accidents, an explosion or rapid deflagration occurs and kills people. Although accidents with natural gas (LNG — methane — CH_4), as distinct from liquefied petroleum gas (LPG — propane), are rare (since methane rises rapidly and does not collect to form an explosive mixture), a large accident with LNG is as likely as a large accident with LPG and could be very bad. The fuel, *if mixed with air,* would be in its most combustible state and very liable to explode. In contrast, nuclear fuel is not so easy to explode. A large modern LNG tank contains enough energy to set off an explosion that is 30 times the size of the explosion at Hiroshima.

Many anti-nuclear power rallies have opened with a picture of a mushroom cloud from a nuclear bomb test, suggesting that a nuclear power plant is always in danger of explosion. It is vital to explain constantly and carefully that a nuclear power plant cannot explode like a bomb. It is not easy to configure uranium to make it explode and, in a power plant, uranium is configured to *prevent* it exploding. The concern about safety is that a power plant might be destroyed and that radioactive material might enter the environment where it might impact people and cause adverse effects upon public health. In principle, most of the radiation protection regulations are to cope with radioactive releases in case of an accident. In the nuclear field so far, the record has been outstanding, with no loss of life to anyone in the public from an accident at a licensed facility outside the former Soviet Union.

The (fortunate) lack of a large historical database poses a dilemma for estimating the probability of a nuclear power accident. We can take the measured accident frequency worldwide and apply it to all reactors in the world, or we can attempt to calculate the frequency. The public, and many sophisticated people who are nonetheless unaware of the details of such calculations, will use only the first method. If we take all the power reactors in the western world and exclude the Chernobyl power plant accident, we have no immediate deaths, and a calculated maximum of one cancer from the accident at Three Mile Island. The total number of years of operation of large reactors is about 3000 for 1 GW(e) plants (3000 GW(e)·a). The calculational method introduced by Rasmussen in 1975 [3] was strongly attacked and even now is not widely believed to be meaningful. This is an issue which must be addressed continually.

The *consequences* of a nuclear power accident are also much in dispute. It has become conventional among experts to include delayed effects on health (such as cancer incidence) together with the immediate direct deaths in tabulations. While this is a good 'conservative' approach, it is misleading when it is not applied consistently for different fuel sources. This becomes clearer when the effect of fine particulates upon health (issue (b)) is considered (see Section 3). Accordingly, I believe that it is desirable to list separately prompt or immediate deaths (within a month) and delayed deaths.

Even in the Chernobyl accident there was no immediate loss of life to the public by acute radiation sickness (death within one month). There were 32 reported immediate 'occupational' deaths among the plant workers and firemen, and probably as many unrecorded deaths among the army and others. Official estimates by the United States Department of Energy (USDOE) of the expected delayed effects of cancer are about 20 000 cases worldwide [4, 5]; these were estimated using a linear, proportional dose response relationship. But Hohmeyer [6] made what I believe to be an unrealistic estimate of 300 000 cases of cancer due to Chernobyl, which is 15 times higher than the above figure. Furthermore, he assumed (incorrectly) that every core melt accident will lead to an accident as big as that at Chernobyl, notwithstanding the experience that the accident at Three Mile Island did not lead to such an accident. This led to a high estimate of 150 deaths per GW(e)·a, which was repeated with approval in a study of the effects of nuclear power on health [9] and without comment by the Office of Technology Assessment [8]. But it is not sensible to assume that all accidents are equally bad and to multiply the probability of a severe accident by its consequence. It becomes essential to describe the sum of that product for accidents of different sizes. Western reactors are very different from the RBMK type reactor at Chernobyl, and it would not be appropriate to assume that every core damage or core melt leads to such a disaster. The science of calculating accident frequency has been greatly developed over the last 20 years and leads to estimates of the overall death rate that are over ten thousand times smaller — 0.001 to 0.01 per GW(e)·a. These are calculated delayed deaths caused by a presumed increase in cancer incidence.

Hohmeyer [6] and Ottinger et al. [7] have not withdrawn or modified their predictions and these play a considerable part in moulding public opinion. They must be very carefully addressed. Unless and until the public understands that these authors are completely wrong, the effect of a nuclear power accident will remain a controversial subject. International work on understanding the consequences of Chernobyl will therefore remain of crucial importance. Another important and simple concept that can help is to expect many accidents of small consequence before expecting an accident of large consequence (although Chernobyl was a partial exception). Loss of life is only expected for 10% of core damage (core melt) accidents, and severe loss of life is only expected for one accident in 100 accidents.

Many members of the public distrust the calculations of nuclear accident probability and do not understand what the calculations mean. This confusion has been deliberately fostered by many anti-nuclear groups. Yet the method of calculation is simple to describe, and its limitations, while important, are not unique to nuclear power. One must first admit, as one cynic commented, that "it is difficult to make predictions — especially for the future". The safety of nuclear power plants was first addressed in the United States of America by what the US Atomic Energy

Commission called 'defence in depth'. The method consists of trying to imagine the worst possible accident caused, presumably by a failure of some component. Then one devises a safety device to prevent it happening. Then one devises mitigation steps (a containment or strategic location) to mitigate the effects if the safety device fails also and the accident occurs. When this approach is systematically applied, it becomes possible to identify those accident scenarios (starting, for example, with fire or earthquake) in which all systems fail simultaneously. This procedure allows some checking to be done; if the 'precursors' to an accident happen only rarely, so that the safety device is rarely called upon, then we can be sure that the accident rate is correspondingly diminished. In the nuclear field so far, the record has been outstanding, with no loss of life to anyone in the public from an accident at a licensed facility outside the former Soviet Union.

3. EFFECT OF PARTICULATE AIR POLLUTION AT THE PRESENT LEVELS

There is no doubt that high doses of radiation have led to acute radiation sickness and death; doses just less than these have led to cancer. But there is much more doubt about whether the low doses that arise from normal operation of nuclear power plants, and even doses to most of the people exposed in accident conditions, lead to any health problems. However, it is conventional, for prudent public policy, to assume that there is a linear relationship between dose and response, so that even small doses, if widely spread over a population, can produce an appreciable response. This assumption was originally suggested by Crowther [9] and for many years was only made by those concerned about radiation exposure. This led to an (incorrect) feeling that anything involving radiation is uniquely dangerous. It is now realized that this assumption is probably equally valid (or invalid) for other carcinogens, particularly if there is an appreciable background, of the same cancer [10]. Recently, it has been realized that linearity may also apply to many other situations, such as particulate air pollution [11].

The effects of fossil fuel use on public health are primarily those of air pollution: the liberation of gases from power plants as a result of fossil fuel burning. Burning of fossil fuels results in emission of gases from incomplete combustion as well as gases from impurities. There is a marked difference between fossil fuel plants and nuclear plants in these respects. The emissions from fossil fuel plants occur in ordinary operation and are continuous, whereas the only important emissions from nuclear plants occur in accident situations.

The problems of pollution from coal were noticed as early as in the 17th century [12]. There is no doubt that air pollution and in particular the burning of coal has killed members of the public outside power plants when air pollution levels were high [13]. There is controversy about how to extrapolate these known hazards to the lower levels of today. In 1970, many scientists thought that *present day* air pollution in the eastern USA or in northern Europe affects 1% of the people exposed. But, in an influential 1979 review, several prominent British scientists systematically discounted the evidence presented in the studies carried out so far, which are classified by epidemiologists as 'ecological' studies [14]. These scientists concluded that the health effects of particulate pollution at low concentrations could not be 'disentangled' from health effects of other factors. The 1982 report by the Environmental Protection Agency, which expounded the reasons for the change to a PM_{10} standard, stated that "the relationship between long-term exposure to air pollution has been extensively studied, but few of the studies provide sound or consistent findings sufficient to make quantitative conclusions". A major (unstated) reason for dismissal of the findings was the (correct) observation that, by 1980, the visible air pollution in many major cities (Glasgow, London, Moscow, Pittsburgh) had already been much reduced compared with that in the 'black periods' of the first half of the century. No Government took any major action.

However, there is now much stronger scientific justification. Exposure of animals to combustion products elucidates possible mechanisms [15]. Moreover, two epidemiological cohort studies avoided mistakes that led to many of the criticisms that applied to the ecological studies. The first was the "Six Cities Study" [16], involving a 14–16 year prospective follow-up of 8111 adults living in six US cities (five of which are: Harriman, TN; St. Louis, MO; Steubenville, OH; Portage, WI; and Topeka, KS), selected to be representative of the range of particulate air pollution. Measurements were made of total suspended particulates (TSP), PM_{10}, $PM_{2.5}$, SO_4, H^+, SO_2, NO_2 and O_3 levels. Although the TSP concentrations dropped over the study periods, the fine particulate and sulphate air pollution concentrations were relatively constant. The most polluted city was Steubenville; the least polluted cities were Topeka and Portage. The differences in the probability of survival among the cities were statistically significant ($P = 0.001$). The mortality risks were most strongly associated with cigarette smoking, but, after controlling for individual differences in age, sex, cigarette smoking, body mass index, education and occupational exposure, the differences in relative mortality risks across the six cities were found to be strongly associated with the air pollution levels in those cities.

These associations were stronger for respirable particles and sulphates, as measured by PM_{10}, $PM_{2.5}$ and SO_4, than for TSP, SO_2, acidity (H^+) and ozone. The association between mortality risk and fine particulate air pollution was consistent and nearly linear, with no apparent 'no effects' threshold level. The adjusted total mortality-rate ratio for the most polluted of the cities compared with that for the least polluted city was 1.26 (95% confidence interval (CI): 1.08–1.47). Fine particulate air pollution was associated with cardiopulmonary mortality and lung cancer mortality, but not with the mortality due to other causes analysed as a group.

The results are summarized in Table I and the values are substantially higher than those in one of the best earlier 'ecological' (population) studies. This difference

TABLE I. COMPARISON OF STUDY RESULTS

Study type	Evans et al. [16] Ecological (population) study	Dockery et al. [17] Cohort study
Sulphate coefficients		
Annual deaths/million per $\mu g/m^3$ sulphate	37.2 ($\pm$19.0)	178.8 ($\pm$91.2)
Converted to PM_{10}: Annual deaths/million per $\mu g/m^3$ PM_{10}	9.3 ($\pm$4.8)	44.7 ($\pm$22.8)
Per cent increase in deaths per 10 $\mu g/m^3$ PM_{10}	1.1% ($\pm$0.6%)	5.9% ($\pm$3.0%)
Particulate matter		
Annual deaths/million per $\mu g/m^3$ PM_{10}	6.4 ($\pm$3.6)	52.3 ($\pm$26.7)
Per cent increase in deaths per 10 $\mu g/m^3$ PM_{10}	0.8% ($\pm$0.4%)	7.0% ($\pm$3.6%)

Note: The results of Dockery et al. were reported as mortality rate ratios, but they were converted to estimates of deaths per $\mu g/m^3$.

suggests that the cohort study is able to estimate the effects of air pollution with more accuracy. Ecological studies are averaging the observed effects over the affected population; therefore, lower rates would be expected for these studies compared with those in the cohort studies.

Similar results were found in a second, larger, prospective cohort study [18]. Approximately 500 000 adults, drawn from the American Cancer Society (ACS) Cancer Prevention Study II (CPS-II), who lived in 151 different metropolitan areas in the USA, were followed prospectively from 1982 through 1989. Individual risk factor data and vital status data over 8 years were collected. Ambient concentrations of sulphates and fine particulates, which are relatively consistent indoors and outdoors, were used as indices of exposure to ambient particulate air pollution from combustion sources. Both fine particulates and sulphates are used as indices of pollution from combustion source particulates, which is considered by many to be a likely agent. Air pollution from sulphates and fine particulates was associated with a difference of approximately 15–17% between the total mortality risks in the most polluted cities and those in the least polluted cities.

The adjusted mortality-rate ratios (and 95% CIs) of total mortality for the most polluted areas compared with the least polluted ones equalled 1.15 (1.09–1.22) and 1.17 (1.09–1.26) when using correlations with sulphate concentrations and concentrations of particulates, respectively. A simple application of these results to the continental USA suggests that 70 000 persons die early (have their lives shortened) through air pollution. I assume that one third, or 20 000 deaths, arise from the existing coal fired electricity generation (about 200 GW·a), which gives a coefficient of 100 deaths per GW·a. *This dwarfs all other health problems of fuel use.*

A general model which might describe the effect is that the air pollution reduces the lung function in an irreversible way. The lung function declines with age and, in the presence of pollution, it could fall to a dangerous level, with all sorts of ailments occurring at an earlier age than otherwise. It is easy to see geometrically that the 'loss of life expectancy' is directly proportional to the assumed lung damage, and the death rate is also proportional to it. This is a delayed effect that is not easy to influence after the initial lung damage, similar to the delayed effect of cancer mortality after a nuclear power plant accident. The magnitude can be summarized by saying that air pollution, mostly from coal burning, but also somewhat from oil burning, causes more effects on public health than would a Chernobyl-size nuclear accident every year.

4. PROBABILITY THAT CARBON DIOXIDE EMISSIONS WILL CAUSE GLOBAL WARMING

The Earth is a greenhouse; heat is absorbed from the sun, but the infrared radiation re-emitted by the Earth is trapped by a number of 'greenhouse gases': water vapour, carbon dioxide, methane, nitrogen oxide and fluorocarbons. This makes the world warmer than it would be otherwise and therefore sustains life on the planet. As carbon dioxide is emitted from fossil fuel burning and the concentrations increase, the greenhouse effect can become larger and this can result in global warming, which can change life on the planet considerably.

Fourier [19] first noticed that carbon dioxide had this property, and Arrhenius [20] made the first detailed calculations in 1896. The greenhouse gases carbon dioxide and methane come primarily from energy use. Every time a carbon atom is burnt, a carbon dioxide molecule is produced. It therefore behooves us to burn fewer carbon atoms, either by changing what we burn or by increasing the efficiency. In both respects the burning of natural gas is touted as being only half as bad as the burning of coal. But that is only half of the story. A greenhouse gas that is 30 times as bad as CO_2 is CH_4, for which even 3% leakage anywhere from the well to the burner can double the greenhouse effect, nullifying the advantage over coal. The figures vary, from 10% gas leakage reported to have occurred in a bad British plant [21] to 3% as a standard leakage factor [22]; a very recent World Bank report states that less than 0.1% leakage can be expected with new pipelines. This last statement is parallel to optimistic statements that the rate of severe accidents (meaning accidents with a measurable public health impact) in the new generation of nuclear reactors should be less than one accident in many millions per year — both possibly true and as yet unprovable. It is important to realize that the effect of excess carbon dioxide emissions is a global one, and the citizens living in any country must concern themselves with the full fuel cycle even though a part of it takes place in other countries.

It seems likely that the carbon dioxide concentrations will rise to two or three times the historical levels within the next century. No one knows what the effect will be and there is much controversy, to which I merely refer [23, 24]. But it is generally agreed that we are making, in a time short compared to human existence, a large change in an important climate parameter (carbon dioxide) which can affect the whole globe and we should try to make the change slowly and to understand what we are doing.

In contrast to the burning of any carboniferous fuel, hydropower, solar power and burning of nuclear fuel in a reactor do not emit any carbon dioxide (although, when the full energy chain is considered, there is a small contribution). In spite of the considerable rhetoric at the meeting in Rio de Janeiro in 1992, where the USA committed itself to keeping greenhouse gas emissions to the 1990 levels by the year 2000, and at the meeting in Berlin in 1995, where the USA committed itself to try to reduce these emissions by 20%, the countries of the world are doing nothing to meet the threat of global warming. The principal way to reduce fossil fuel use is by increasing the price. Scientists and economists have suggested a *carbon tax*, to reduce fossil fuel use and to encourage fuel switching. But this was only weakly supported by the US administration and was soundly rejected by the US Congress in 1993. Nuclear power has the potential to replace fossil fuels for electricity generation, but the price of nuclear has doubled in inflation corrected dollars in the last 20 years and the US Government is making no attempt to retain a strong nuclear power programme.

This political situation is likely to remain, unless and until more persuasive scientific evidence is available. In 1995, however, the evidence was becoming less persuasive. Three years ago, the Intergovernmental Panel on Climate Change (IPCC) [25] made estimates of the coefficient relating the effect of doubling the carbon dioxide in the atmosphere on global temperature, and of how long it would be before the world reached such a doubling of carbon dioxide. In 1995, the estimate of the coefficient was revised slightly downwards [26] and the time before the temperature rise occurs was extended. This 'back tracking' after public alarm was raised has therefore legitimately suggested to many members of the public that the scientific experts do not know what they are talking about and should be ignored.

5. THE WASTE PROBLEMS OF FUEL USE

The problems of waste in society are very badly characterized and discussed. Although waste problems are often thought to be ecological or environmental issues, no specific ecological or environmental hazard is usually adduced. Nonetheless, waste problems of all industries have attracted public attention, and the 'solution' of the problem of nuclear waste is often regarded as being essential to the future of nuclear power. A crucial misconception, however, is the common feeling that nuclear waste is uniquely bad. In what follows, I will discuss the limited extent to which this might be true.

Of the fuels used for electricity generation, gas leaves only carbon dioxide and water vapour as wastes, which naturally dispose of themselves. Hydropower leaves water in the liquid form, which is also easy to dispose of. But coal and oil are different. In the USA, 800 million tonnes of coal are mined every year; this means that 800 million tonnes of overburden must be removed and put somewhere. In addition, there are 120 million tonnes of fly ash in the coal, which has to be disposed of, and 20 million tonnes of sulphur compounds. Since the amount of energy from fission of uranium is three million times the amount of energy from burning of coal or any other fossil fuel, the volume or weight of the waste from coal burning dwarfs that of nuclear wastes. Nonetheless, coal wastes are not perceived by the public as a major problem. It is correct, but perhaps an oversimplification and unhelpful, to state that the unique problem of nuclear waste is political rather than technical.

One problem of disposal of nuclear waste is a safety problem. Many people are willing to concede that if nuclear waste is disposed of successfully, there is and will be no problem, as shown in the 'professional' estimates of the effects of nuclear waste upon public health presented below. If there is an accident of some sort at a waste disposal facility, there is the fear that radioactive material will enter the environment, where it will have a large effect on public health. What would be the *likely* effects of a failure of a given waste disposal site, and how do these effects compare with effects, similarly calculated, of coal and other wastes?

There is very little *ecological* effect of *nuclear* waste disposal, in contrast to the possible large regional ecological effects of disposal of chemicals such as arsenic (or even of coal wastes which contain a little arsenic). It is important to realize that the effect on public health is the *only important* effect of any failure to contain the waste. Nonetheless, the criteria that the world is suggesting for the disposal of radioactive waste are stricter than any criterion ever before imposed upon any segment of society. The world is demanding that it be proven that over the next 50 000 years a waste disposal site will not leak enough to cause even a hundred or so cancers in the population around. The difficulties arise in the nature of such a proof for some catastrophe in the future, and in the smallness of the effects being prevented. The disposal of coal waste, which is radioactive, with half-lives comparable to those of the long lived nuclear waste, has to meet no such criteria. Moreover, the sheer quantity of coal waste makes it impossible to take such a stringent approach as we will probably successfully meet for nuclear waste. Although in the perception of many members of the public the waste issue is a problem unique to nuclear power that may prevent its continuation, this is *not* a technical problem. Indeed, many scientists have said that the problem of nuclear waste is the *only* one for which there exists any idea of a sensible long term solution.

Although *no one* has come up with a failure scenario for a projected DOE nuclear waste site which comes close to having an effect equal to that of the Chernobyl accident, accidents *did* occur in Russia at Kyshtym. In the first accident, 2 million Ci of radioactive material, including 500 000 Ci of ^{90}Sr, were dumped into the Techa River [27]. The peasants downstream were not informed, for reasons of military security, and many received radiation doses of 200 rem. In another accident, a facility suffered a chemical explosion, which blew 5 million Ci of radioactivity into the countryside to the north-east. These were accidents in the military complex, not in the civilian uses of nuclear energy. Moreover, although this caused a major effect upon public health and considerable dislocation of people, it is noteworthy that the effects were regional and the details were successfully kept secret from the rest of the world for 35 years. Other regional effects of comparable magnitude came from other, non-nuclear, pollution. A distinction can be made between a military complex in the former Soviet Union, built in a hurry and in secrecy to catch up with the 'wicked' USA, and a civilian complex in the USA. If attention were paid to such distinctions, the direction of the public debate might be changed.

Accidents *have* occurred with coal wastes, which are both toxic and radioactive. On 21 October 1966, a slag heap slid into a school at Aberfan, North Wales, and killed 144 schoolchildren.

Just as with the effects on ecological systems, in spite of the calculations and measurements of experts showing that nuclear wastes are the *only* wastes for which there exist good technical solutions for disposal (because of the ability to keep the volume small), they are not so perceived. Possible reasons may include the following points:

- Nuclear fission is perceived as particularly complicated and it is believed that the claims made cannot be trusted;
- There is very little understanding of the issues among administrators, politicians and the public;
- New technologies must not merely be better than old technologies, but a lot better — perhaps perfect.

Public policy must address the issues of perception. They are, as mentioned in the Introduction, *environmentalist* problems rather than *environmental* problems. They are nonetheless real and might be circumvented by logical discussion. In this, the IAEA, preferably together with other energy agencies, has a critical role to play.

6. DOES THE ENERGY USE CONTRIBUTE TO WAR?

This issue is not formally within the purview of this symposium, but it is so important in the public perception of energy issues that it cannot be left out. Does the use of the fuel under consideration increase or diminish the probability of a global (probably nuclear) war?

To many people the most shocking factor in the 1973 'Yom Kippur' war was the oil embargo and the resulting rise in prices. It demonstrated the dependence of much of the world on a volatile region for its fuel supplies. This has led many countries to try to achieve 'short term' energy independence. In this regard, nuclear energy has a very positive effect in the short term because of the fact that three million times more energy is released in nuclear fission by one gram of uranium than is released in the (chemical) burning of one gram of any fossil fuel. Whereas it is hard to find space and it is very unsightly (damaging to the visual environment) to store even one year's supply of coal, gas or oil, it is easy, and common, for a power plant to have several years' supply of uranium on hand, already made into fuel rods.

Nuclear energy, by helping countries to achieve energy independence, can have a very important positive effect on the probability of war. This can particularly be the case for islands, such as Japan, Taiwan or the United Kingdom; or for a country surrounded by neighbours with a different ethnic character, such as Armenia. On the one hand, the island country need not go to war to get immediate sources of fuel, and, on the other hand, neighbouring countries will be less tempted to exercise their will with an oil (or gas) blockade.

The implication of many people that the use of nuclear power, and only nuclear power, can lead to nuclear war is false. Any global war is likely to be a nuclear war. Fuel supplies and energy use generally are important to man's activities and wars have been fought over their use. In 1910, the Government of the UK bought a controlling interest in the Anglo-Iranian oil company to guarantee access to oil for its fleet. In 1914, the Japanese joined in the first world war — against Germany and on the side of the UK, to safeguard supplies of coal from Manchuria. In 1941, the Netherlands and the USA put an oil embargo on Japan, in an endeavour to persuade them to leave China, but, when oil was running low, Japan bombed Pearl Harbor, and went south to take the oil they needed from Indonesia. In 1991, the Republic of Azerbaydzhan shut off the gas pipeline running through its territory from Russia, in an attempt to prevent Armenia from helping their ethnic brothers in Nagorno-Karabakh; and, also in 1991, the whole world (the United Nations) fought a war to overturn the Iraqi takeover of Kuwait — a war which was largely a war about supplies of oil.

Many people have argued that the very existence of nuclear electric power encourages proliferation of nuclear weapons throughout the world and increases the chance of nuclear war. The connection between the civilian use of nuclear fission and the military use of nuclear energy is real. Sir Alan Cottrell [28] argued that it was the only legitimate issue about nuclear energy, which seems to dominate public thinking in a way that few people know how to explain or even address. People transpose their opposition to nuclear power on this ground to making incorrect or illogical statements about one of the other 13 items mentioned in Section 1. It is therefore essential in any discussion of the potential environmental impacts of nuclear power to discuss the connection between electricity and bombs.

The USA built an atomic bomb in four years, starting from scratch, and not being absolutely sure how to proceed. Now that most of the information is public knowledge, a national determination and some industrial infrastructure is all that is needed. A moderately industrialized country can obviously make a weapon unaided within 10 years. If other countries of the world wish to prevent this, they can do so; the first step is to acquire information about what a country is doing; the second step is to try to prevent it by agreements and sanctions. The worldwide influence of the nuclear industry can be used, if the parties so wish, in both these steps. Now that the 'cold war' is over, professional societies and others can make openness and peacefulness a condition for co-operation. I believe that, with care, the argument that the use of nuclear energy leads to war, or even to proliferation of nuclear weapons, can be inverted, and that the existence of a worldwide nuclear power community can inhibit the development of nuclear weapons [29].

In this connection, the renewal of the nuclear Non-Proliferation Treaty (NPT) in 1995 for an indefinite period is a fantastic success, especially for the skilful chairman of the NPT conference. But the immediate resumption of bomb testing by France and China, even if for a limited time and even if it is not actually contrary to the letter of the treaty, is contrary to the spirit of what each country signed in May 1995. The way in which spokesmen for each country emphasize that there is no (direct) environmental effect (as if this were the important issue) and the fact that environmental activist groups such as Greenpeace oppose the tests primarily on this issue have confused an already confused situation. The actions and words will create far more public confusion in this respect than any possible good that this Symposium can do.

In this connection, I also call to your attention the example given, as early as 1967, by Dr. Joseph Rotblat, winner of the 1995 Nobel Peace Prize. While campaigning tirelessly in 1967 for a cessation of atmospheric atomic bomb tests, he urged everyone to reject the support of Dr. Ernest Sternglass who was claiming that fallout from these tests was contributing to infant leukaemia and mortality even in the USA. The point is that the struggle for peace (and I would add for a safe environment) is not a struggle to be won by incorrect but superficially attractive argument in one debate. It is a struggle where only the truth can help us, and a falsehood, once accepted to stop bomb tests, can then be used to stop beneficial uses of nuclear fission, on which Dr. Rotblat has worked during much of his productive life.

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IMPLEMENTATION OF COMPARATIVE ASSESSMENT

(Session 4)

Chairman

D. ZHOU
China

COMPARATIVE ASSESSMENT IN POWER SECTOR DECISION SUPPORT STUDIES
Findings from the DECADES Project

L. BENNETT
Planning and Economic Studies Section,
Division of Nuclear Power,
International Atomic Energy Agency,
Vienna

E. BERTEL*
Nuclear Development Division,
OECD Nuclear Energy Agency,
Issy-les-Moulineaux,
France

M. DERROUGH
Planning and Economic Studies Section,
Division of Nuclear Power,
International Atomic Energy Agency,
Vienna

Abstract

COMPARATIVE ASSESSMENT IN POWER SECTOR DECISION SUPPORT STUDIES: FINDINGS FROM THE DECADES PROJECT.

The paper presents lessons learned, preliminary conclusions and findings from country case studies carried out in connection with the DECADES project in the framework of an IAEA co-ordinated research programme (CRP) established in December 1993. More than twenty case studies are being carried out within the CRP in different countries and regions of the world. Final reports from these studies will be published in 1996. The main objectives of the CRP on "Case studies to assess and compare the potential role of nuclear power and other options in reducing the emissions and residuals from electricity generation" are: to identify the issues that analysts and policy makers have to address in decision support studies for the power sector; to investigate methodologies and computerized tools that can be used for carrying out such studies; to provide a co-operative framework for undertaking case studies in different countries; and to illustrate by concrete results the influence of comprehensive comparative assessment on choices of energy mixes for electricity generation. The paper describes the process adopted for implementing the CRP, with the objectives of sharing information and

* Formerly Planning and Economic Studies Section, Division of Nuclear Power, International Atomic Energy Agency, Vienna.

experience between the scientific teams and of enhancing the efficiency of the different projects. An overview of the scope and objectives of the different studies is given, and priority issues in different countries and regions with regard to electricity system expansion policies are highlighted. Issues related to the implementation of comparative assessment in the process of electricity system analysis for decision making purposes are examined, drawing from the experience of the participating scientific teams. In particular, the paper points out difficulties encountered in data collection and consistency checking, choosing adequate methodologies and analytical models, and using the tools in an efficient way aiming towards providing relevant guidance to decision makers on the overall merits of different options and strategies for electricity system expansion. Finally, the paper gives a brief summary of preliminary results, conclusions and findings from the different case studies, focusing on lessons learned from the research carried out. The conclusions provide recommendations on further research to be undertaken in a co-operative framework for implementing comparative assessment in policy making for the power sector and give some views regarding the influence that comparative assessment of the economic, social, health and environmental aspects may have on the choice of energy mixes for electricity generation.

1. INTRODUCTION

In the framework of the DECADES project, country case studies were undertaken in order to assist Member States in implementing comparative assessment in the process of decision making for the power sector. The main objectives of the DECADES case studies are to:

— Identify and explore key economic, social, health and environmental issues that Member States have to address in policy making for electricity system expansion;
— Provide a co-operative framework for sharing information and experience between scientific teams from different Member States working on the subject matter;
— Illustrate the use of different methodologies, models and computer tools for comparative assessment in decision support studies; and
— Give feedback for enhancement of comparative assessment tools that better meet the information needs of policy makers.

In this context, the IAEA established, in December 1993, a co-ordinated research programme (CRP) on "Case studies to assess and compare the potential role of nuclear power and other options in reducing the emissions and residuals from electricity generation". Proposals for participating in the CRP were submitted to the IAEA by institutes from Member States. These were reviewed and technically evaluated, taking into account the relevance of their scope and objectives in connection with the DECADES project. More than twenty projects were selected, and most studies started during the first semester of 1994. All projects will be finalized by mid-1996 or earlier.

Although budget, manpower and time frame constraints prevented the IAEA from supporting all the relevant proposals submitted by Member States, a wide range of topics are being addressed in the case studies, covering different countries and regions and also different socioeconomic situations. Because of the goal of the CRP to investigate real-life problems and issues in country specific contexts, the scope and objectives of the different studies vary; however, they all focus on comprehensive comparative assessments of electricity generation options and strategies in support of decision making.

Interim or final results from some of the DECADES case studies are presented in detail during this Symposium, either orally or in the poster sessions. Several case study reports have already been published by the institutes that are responsible for their achievement. Upon completion of all the projects, a final report, covering the main results, findings and conclusions from the case studies and lessons learned from the CRP, will be published by the IAEA in the DECADES project series.

2. CO-OPERATIVE FRAMEWORK AND WORKING MODE

The establishment of a CRP offers a scientific and administrative framework for undertaking projects in different Member States within an overall scope, time frame and set of objectives defined by the IAEA. The participating scientific teams have opportunities to define their studies, within the overall objectives of the CRP, to meet their specific interests and high priority issues. The different studies are reviewed collectively by representatives from the study teams and the IAEA, during Research Co-ordination Meetings (RCMs) that are convened at about one year intervals.

The main role of the IAEA within a CRP is to provide a forum for exchange of information and experience between the different teams, and technical assistance whenever necessary. Some financial support is also provided by the IAEA to cover part (typically only 10–30%) of the expenses incurred by national institutes in connection with carrying out the studies, such as acquiring equipment, documentation and computer models, staff training and travel.

National scientific teams are responsible for raising adequate funding to support their share of the costs associated with the study and to ensure that the scope and objectives of their project deal with topics and issues of interest in their respective countries. Whenever relevant, national teams are encouraged to establish mechanisms of co-operation between different national experts, institutes and organizations in order to benefit from a broad range of expertise and know-how in various fields, e.g. economics, electricity generation technology characterization and impact assessment.

The efficiency of a CRP relies mainly on the co-operative framework and mechanisms put in place between the teams and the IAEA. With regard to the DECADES case studies, owing to the large number of projects and the wide range of topics addressed, it was especially important to establish and maintain a close co-operation, aiming towards extensive exchange of information and feedback from experience, among the participants and between the teams and the IAEA.

Therefore, in addition to the RCMs, topical meetings and workshops were convened on an ad-hoc basis in order to address specific topics and difficulties encountered in different projects. Topical meetings were held on issues related to data collection and consistency checking for the establishment of country specific technology inventories necessary for carrying out relevant electricity system analysis and expansion planning for decision making purposes. The selection of adequate analytical models to be used in the respective studies, when applicable, was also discussed jointly. Preliminary results were discussed at an early stage of the studies, aiming towards assisting the teams in focusing on priority issues that could be comprehensively addressed within the time frame of the CRP.

The exchange of information, data and experience during the RCMs and additional meetings proved to be especially effective for carrying out studies dealing with transboundary issues, such as interconnection of electricity networks or atmospheric pollution. The process of presenting interim results, identifying difficulties encountered by different teams and pointing out ways and means to address specific issues, allowed the different teams to benefit from each other's experience and to enhance the efficiency of the overall programme.

The assistance and guidance from the IAEA covers different aspects of support to national experts participating in the programme, in particular on approaches, methodologies and computer tools adapted to the specific topics a given team wanted to address. Assistance and on-the-job training was offered in so far as feasible in the use of the IAEA's models for electricity system analysis and comparative assessment. In particular, efforts were made to disseminate to the teams the databases and computer tools developed within the DECADES project and to provide them with guidance on their use. During the final phase of the projects, in the process of reviewing reports from the case studies, the IAEA endeavoured to help the teams in assessing the soundness of their results and in presenting them in a comprehensive and synthesized form, having in mind the needs and requirements of the decision makers who are the target audience for these reports.

3. SCOPE AND MAIN OUTCOMES FROM THE CASE STUDIES

Although each case study is country specific, all studies were designed in the context of increasing awareness of the need to address health and environmental issues in the process of designing sustainable electricity supply strategies. Energy policies in most regions of the world are aiming towards mitigating the direct and indirect adverse effects of energy systems, taking into account the full energy chain, from primary resource extraction through electricity generation to waste management and disposal. In particular, Governments have taken steps to sign international agreements and conventions related to air pollution mitigation, and are setting up national environmental protection standards and regulations that energy producers have to meet.

In this connection, the DECADES case studies have the primary objectives to investigate alternative electricity supply strategies and to analyse the technical and economic feasibility of switching to less polluting energy mixes for electricity generation. The studies fall within three main categories with regard to their scope and objectives:

- Establishing a comprehensive technology inventory for the country, covering power plants and fuel chain facilities currently in operation and those which are considered as options for electricity system expansion within the next two to three decades;
- Assessing and comparing different energy sources and power plant types;
- Assessing different policy measures for pollution mitigation (e.g. CO_2 taxes; standards and regulations).

3.1. Country specific technology inventories

Comparative assessment of different electricity generation options and strategies requires access to reliable and up-to-date information on existing electricity technologies in the country as well as on the different technologies that can be considered for the future. Most of the national institutes participating in the CRP recognized earlier that the data available to them were not complete or consistent enough to support comprehensive comparative assessment of different options and strategies in the power sector. Therefore, the first step was to carry out a technology inventory and to establish a country specific database (CSDB), using the reference technology database (RTDB) computer structure.

Some fifteen CSDBs have been established, covering technologies at the different steps of the electricity generation chains in the respective countries. The teams have focused their efforts on collecting and checking the consistency of data for facilities at all levels of the different energy chains used or planned to be implemented in the country. They have succeeded in compiling relevant information, drawing from databases available in the country and seeking the co-operation of a wide range of experts in the fields of electricity generation technologies and environmental impact assessment. However, some institutes have faced problems in collecting information from all the organizations and companies involved, particularly in countries where electricity generation and fuel supply are under the responsibility of several State owned and private companies. Also, in some countries, it proved difficult to collect data on emissions and residuals from power plants and fuel chain facilities.

Once established, the CSDBs will be used by the teams for completing their respective case study through carrying out comparative assessment of alternative electricity system expansion strategies. Furthermore, it is expected that the CSDBs will be maintained and updated for further utilization by Government agencies and utilities in other studies related to electricity system analysis and expansion planning. Therefore, the work already carried out will have lasting benefit to the countries involved.

3.2. Comparative assessment of different energy sources and power plant types

The analyses carried out in this category of case studies rely on different analytical models and computer tools, including those developed and disseminated by the IAEA, such as WASP and ENPEP. In most studies, the emphasis was put on economic and environmental aspects of the different options and strategies considered, although some health effects were also analysed. The outcomes are aiming towards identifying electricity generation strategies that would meet the objectives of environmental protection, in particular to reduce atmospheric emissions at acceptable cost. The results obtained so far allow some tentative findings to be presented and conclusions to be drawn that seem to apply to most countries.

Significant reductions of emissions and other environmental burdens can be obtained by improving the efficiency of existing facilities at different levels of the energy chains, including the fuel conversion and transportation steps as well as the power plants. Rehabilitation of existing power plants, in particular by adding pollution control technologies, is often a cost effective measure for mitigating environmental impacts. Improving the overall energy system efficiency by promoting cogeneration is identified as a very cost effective option in many countries, especially where heat distribution networks already exist for district heating.

In many countries, especially developing countries and countries in transition, coal fired power plants remain the least cost option for electricity generation. However, in some cases, these plants are emitting atmospheric pollutants such as carbon dioxide, sulphur oxides and nitrogen oxides at levels exceeding even the current national and international norms and regulations, and the limitations are expected to become even more stringent in the near future. Therefore, electricity system expansion strategies aiming at alleviating atmospheric emissions often require rehabilitation and/or early retirement of coal fired power plants. New coal fired power plants will need to rely on advanced, cleaner technologies, such as fluidized bed combustion, and/or will need to be equipped with pollution abatement systems.

Combined cycle gas fired power plants are identified as an attractive option from the environmental and economic viewpoints in a number of countries. Renewable energy sources other than hydropower are seldom considered as viable large scale options for electricity generation, owing to their early stage of industrial development and their high costs. In those studies where nuclear power was considered, it appears to be cost effective for reducing emissions of SO_2, NO_x and CO_2. For example, some of the studies show that, although CO_2 emission reduction targets could be achieved without nuclear power, its use would lead to significantly lower costs. In some other studies, the high investment cost of nuclear power was identified as a potential barrier to its deployment; however, imposition of stringent CO_2 emission reduction targets would require the use of nuclear power in order to displace lignite or coal fired power plants. In general, the studies showed that the possibilities for CO_2 emission reduction in the electric power sector would be very limited without the use of nuclear power.

Macroeconomic and environmental impacts of strategies relying upon a large deployment of nuclear power have also been analysed. While the environmental benefits from such strategies in terms of atmospheric emission reduction were to be expected, some other advantages also have been identified, such as positive impacts on the growth of the gross domestic product, and on employment and balance of trade in countries with scarce domestic fossil fuel resources. The results showed that, if the large nuclear power programme had not been implemented, the electricity prices would have been significantly higher and would be very sensitive to the prices of imported coal.

It should be stressed that all the studies show that only through energy mixes incorporating a combination of different technology options is it possible to reduce significantly the health and environmental impacts from the power sector. Therefore, all the options that can contribute to this objective have to be considered and implemented when they are viable.

It is also pointed out in most studies that business-as-usual demand scenarios are not compatible with emission reduction goals prevailing at present. Therefore, demand side management measures will be required in order to reduce the energy intensity in all sectors.

3.3. Comparative assessment of policy measures for pollution abatement

In addition to technology choices, policy measures have to be implemented in order to meet the objective of sustainability. Policy measures include: privatization/ deregulation of the energy sector; energy interchanges between neighbouring countries; CO_2 taxes; and internalization of external costs. Most of the measures imply international co-operation, e.g. technology adaptation and transfer, and/or international agreements, e.g. conventions on emission standards and norms.

Decision support studies can be especially relevant in order to assess the overall macroeconomic, social and environmental impacts of measures that are under consideration for alleviating specific environmental burdens. For example, when considering a tax on CO_2 emissions, all the effects on the country's economy should be analysed and compared with the potential reduction in emissions that the tax would achieve. Several DECADES case studies addressing such issues illustrate their importance for analysts and decision makers.

Although national Governments continue to play a leading role in energy policies, in many countries there is a trend towards deregulation and privatization of the power sector, aiming towards increasing its efficiency through market mechanisms. This would normally lead to a restructuring of the power sector, shifting from rather centralized systems with few, mostly State owned or State controlled, utilities to a conglomerate of mainly privately owned electricity producers. Privatization and deregulation are likely to have a major impact on the choices of fuels and power plant types. Concerns have been raised about the willingness of private investors to take into account long term global issues such as environmental impacts. One of the DECADES studies analysed the environmental implications of privatizing the country's electricity sector. The study compares emissions and residuals resulting from two contrasting strategies, reflecting either the private investor priorities, e.g. low capital investments and high rate of return, or the Government priorities, e.g. addressing long term sustainability concerns. The results lead to the conclusion that, even in a privatized electricity industry, integrated planning at the national level is needed in order to capture the environmental dimensions.

Interconnected transmission networks allowing electricity imports and exports across borders of neighbouring countries are common practice in most regions of the world. These exchanges have proven to be technically and economically beneficial for load shifting and for reducing the total generating capacity required. The impacts of electricity interchanges between neighbouring countries have been analysed in one of the case studies, comparing the economic and environmental aspects of alternative scenarios with and without interconnection. The study shows that optimization of the electricity exchange between countries has significant benefits through reducing investments, operation costs, fuel consumption and emissions in the power sector of each country.

The risk of global climate change is a key issue for policy making in the power sector. Although large uncertainties remain on climate mechanisms and the impacts of global climate change, it is generally recognized, in the light of the precautionary principle, that reducing CO_2 emissions is a worthwhile objective. Besides norms and regulations, carbon or energy taxes are contemplated by some Governments as a means to reduce CO_2 emissions. In this context, several studies analysed the impact of a 'CO_2 tax' on electricity system expansion strategies and their optimization. Obviously, carbon taxes as well as CO_2 emission limits lead to energy mixes that have a smaller share of coal fired power plants. In most cases, renewable energy sources other than hydropower were found not to be economically competitive. Therefore, the introduction of a CO_2 tax leads to significantly higher deployment of nuclear power in the economically optimized expansion plan. Through the use of sensitivity analysis, it was possible to estimate the optimal level of the CO_2 tax that would minimize the cost of achieving a specified reduction in CO_2 emissions.

The social, health and environmental impacts might be integrated into the comparative assessment of alternative options by internalizing external costs, in so far as they can be estimated. Such a policy requires that the Government creates a planning framework in which all damages and benefits from electricity production are taken into account by the producers and are reflected in their costs and prices. Although this approach does not eliminate the damages directly, it provides an economic incentive to reduce them. However, this approach has been seldom used so far, since it requires identifying and valuing all the residual impacts in order to provide producers and consumers with the right market signals.

The impact that environmental cost internalization would have on the electricity producer's choices of alternative options and strategies for electricity generation was analysed in one case study. It was found that, although the utilities had to adapt their decision making process in order to address external costs, the planned energy mixes were affected only marginally, since the economic ranking of alternative options was not very strongly affected by the external costs, which could be valued and internalized. It is particularly noteworthy that the inclusion of external costs did not lead to selection of renewable energy sources. In spite of the results showing that, in the cases studied, the inclusion of external costs did not strongly influence the outcome, it was concluded that there is a need for further research on identifying and valuing externalities.

4. LESSONS LEARNED AND THE WAY FORWARD

Besides the results obtained by the different teams and their relevance for analysts and policy makers, the DECADES case studies provide some lessons that can give guidance on the use of comparative assessment in decision making for the power sector.

The CRP has met with high interest from Member States. A large number of teams from countries facing a variety of problems and concerns with regard to policy making in the power sector are participating in the programme. The studies addressed a wide range of issues relevant in different regions and socioeconomic contexts. However, the review and analysis of the scopes and objectives of the different studies show that some key issues seem to be common in most countries. This analysis provides guidance for focusing further co-operative studies on a limited number of high priority topics that are relevant for a majority of Member States. Environmental issues in general, and reducing atmospheric emissions in particular, clearly are high on the agendas of decision makers in most Member States. Therefore, comparative assessment of technological options and policy measures for reducing atmospheric emissions and mitigating their impacts seems to be a relevant focus for future co-ordinated programmes of work.

These studies have shown that the various databases on different energy sources and technologies need to be carefully checked for consistency, since several researchers reported finding very different values in different databases, even for supposedly the same technologies. The researchers also emphasized the need for each country to establish their own databases containing data specific to the country.

Since the DECADES case studies were aiming towards exploring and investigating a broad range of issues, it proved somewhat difficult to compare the results obtained in different projects and to draw some generic findings or conclusions from them. However, the overall experience from the CRP demonstrates that the efficiency of information exchange is significantly enhanced when the teams are dealing with similar topics although in different specific situations. Harmonizing the frameworks and the methodological approaches adopted in the different projects would also be desirable in view of the necessity to compare results obtained in various country specific situations. Furthermore, the relevance and quality of the technical support provided to the teams, as well as sharing of experience between the teams could be significantly enhanced if the studies undertaken would rely on the use of similar models and computer tools.

The experience of teams in using the presently available computer tools for comparative assessment of electricity generation options and strategies highlighted that, although these tools proved to be extremely useful for carrying out studies, none of them could meet entirely the requirements of the analysts. On the basis of experience with the DECADES case studies, recommendations on desirable enhancements of analytical models and computer tools have been drawn up and could serve as guidance for further research and development in this field.

With regard to co-operative mechanisms, a major lesson learned from the CRP is the importance of strengthening, in so far as feasible, the exchange of information and feedback at each stage of the studies. This results in enhancing the synergy between teams from different regions and with different levels of expertise and know-how. Each team is able to benefit from the interim results and findings of the other teams. In this connection, the co-operative framework should be flexible enough to allow for convening topical meetings, workshops and training sessions on an ad-hoc basis whenever necessary.

In the light of these findings, the IAEA has included in its provisional programme and budget for 1997–1998 a new CRP on case studies that will focus on addressing environmental issues with emphasis on assessing cost effective measures for reducing atmospheric emissions from the power sector. It is intended that studies undertaken within this CRP will use, to the extent possible, the databases and computer tools developed and implemented within the DECADES project.

5. CONCLUDING REMARKS

The results from the DECADES case studies, summarized in this paper and presented in more detail during the Symposium, demonstrate the effectiveness of the CRP. The number of participating teams shows that the subject matter is of high interest to Member States and that the co-operative framework offered by the IAEA was found to be relevant and helpful. In this connection, although financial support might in some cases be a prerequisite for a national team to undertake a study, exchange of experience and technical assistance are the key elements for the effectiveness and success of joint undertakings.

Since the present CRP will be finalized only in mid-1996, it is premature to draw final conclusions from the case studies regarding the use of comparative assessment in policy making for the power sector. However, some preliminary findings seem to emerge from the interim results obtained so far.

The main alternatives for reducing emissions and burdens from electricity generation appear to be retrofitting of existing fossil fuelled power plants, enhancing the use of cogeneration and, whenever technically and economically feasible, developing nuclear power. Renewable energy sources for electricity generation are generally found to be too costly and, in any case, to offer only marginal potential for large scale electricity supply. Barriers to implementation, such as insufficient funding and/or access to advanced technology, were identified in several studies. Therefore, international co-operation for technology adaptation and transfer and for financial support by international development banks or private banks will have a major role to play for the implementation of sustainable electricity strategies.

Bilateral and multilateral co-operation was identified as a key element in reducing environmental burdens, in particular greenhouse gas emissions and emissions of gas causing acid rain. Several studies pointed out that, in order to reduce investments and operation costs resulting from the implementation of mitigation options, the enhancement of co-operation between countries for the development of joint projects would be very effective.

Finally, the importance of policy measures was recognized in most studies, which concluded that technology enhancement alone will not be sufficient to meet the objectives of sustainable development. Therefore, even in a privatized electric power industry, there will be a need for Government involvement in setting overall national policies, in particular with regard to objectives and targets for protecting the environment.

PROGRESS REPORT ON CASE STUDIES CARRIED OUT WITHIN THE UNITED NATIONS DEVELOPMENT PROGRAMME FOR ASIAN CO-OPERATION ON ENERGY AND THE ENVIRONMENT (PACE-E)

T. LEFEVRE
Economic and Social Commission for
Asia and the Pacific (ESCAP)
and
Asian Institute of Technology (AIT),
Bangkok, Thailand

Abstract

PROGRESS REPORT ON CASE STUDIES CARRIED OUT WITHIN THE UNITED NATIONS DEVELOPMENT PROGRAMME FOR ASIAN CO-OPERATION ON ENERGY AND THE ENVIRONMENT (PACE-E).

The major goal of energy-environmental planning (EEP) in the framework of the Programme for Asian Co-operation on Energy and the Environment (PACE-E) is the enhancement of the environmental perspectives in energy planning and policy making in the developing countries of Asia. Three immediate objectives can be mentioned: (1) the strengthening of energy-environmental databases in Asia, (2) the development and application of innovative and effective energy impact assessment methodologies, and (3) the identification of suitable institutional structures that will result in a more transparent treatment of energy-environmental concerns in national energy plans and in subsectoral (e.g. coal, natural gas) development strategies. In the framework of Programme Element I, three sub-activities, to be executed by the Economic and Social Commission for Asia and the Pacific (ESCAP), have been proposed: the main objective of EEP1 is to strengthen the capacities of the methodologies of survey and sample design and the techniques of data processing. The main objective of EEP2 is to assist in the application of methods and tools of sectoral energy demand analysis and scenario building to evaluate energy conservation and fuel switching potentials. The EEP3 activities will consist of the review and application of methodologies and procedures for integrating environmental considerations into energy planning and policy analysis. The direct recipients of this programme will be policy makers, administrators and technicians from 20 Asian countries dealing with energy and environmental planning and management. The paper presents an overview of the implementation and first results of the various sub-activities of the EEP element of PACE-E executed by ESCAP and implemented by the Energy Planning Central Consultant Team of the Asian Institute of Technology.

1. INTRODUCTION

The major goal of energy–environmental planning (EEP) is the enhancement of the environmental perspectives in energy planning and policy making in the developing countries of Asia. There are three immediate objectives: (1) strengthening of energy–environmental databases in Asia; (2) development and application of innovative and effective energy impact assessment methodologies, which will facilitate a conceptually sound consideration of environmental concerns in energy cost analysis and pricing; and (3) identification of suitable institutional structures, which will, among other things, result in a more transparent treatment of energy–environmental concerns in national energy plans and in strategies for subsectoral (e.g. coal, natural gas) development.

In the framework of Programme Element I, four sub-activities have been proposed: EEP1, EEP2, EEP3 and EEP4. However, only the first three activities will be discussed, since they are under the direct supervision of the Economic and Social Commission for Asia and the Pacific (ESCAP) and the Asian Institute of Technology (AIT). All activities in the framework of EEP1 to EEP3, for which contributions will be provided to the Working Group on EEP (WG/EEP) by Asian countries, the United Nations Development Programme (UNDP), the Government of France and possibly other international agencies, take place between October 1993 and December 1997.

The immediate objective of EEP1 is to strengthen the capacities of the methodologies of survey and sample design and the techniques of data processing. Strengthening of the sectoral energy demand analysis and building of scenarios through acquisition of comprehensive and reliable data will assist countries in formulating environmentally sound energy demand management and efficiency improvement policies.

The main objective of EEP2 is to assist in the application of methods and tools of sectoral energy demand analysis and scenario building to evaluate energy conservation and fuel switching potentials.

The EEP3 activities will consist of the review and application of methodologies and procedures for integrating environmental considerations into energy planning and policy analysis.

The direct recipients of this programme will be policy makers, administrators and technicians from 20 Asian countries dealing with energy and environmental planning and management. In addition, representatives of the private sector and universities will be invited to participate in the training activities of the programme. In the framework of the above mentioned sub-activities, in-country teams will be established and EEP sub-focal points (project co-ordinators) will be selected by the Governments of participating countries to carry out in-country studies on the above mentioned subjects. In addition to the transfer of methodologies and procedures through regional training workshops, the Energy Planning Central Consultant Team of AIT (EPCCT/AIT) will guide the in-country teams through on-the-job training and technical and advisory missions in order to implement the national studies. The project is executed by ESCAP and implemented by EPCCT/AIT.

As of September 1995, the three sub-activities are in progress; some activities have already been partly carried out (EEP1 and EEP3) and others are under intensive preparation (EEP1, EEP2 and EEP3). Detailed reports on all activities are being prepared and some of them have been available since the end of 1994 (synthesis and methodological reports, training materials, as well as users' and technical manuals on developed methodologies). All material on methodological developments prepared by EPCCT/AIT was disseminated through training workshops in September 1994 (EEP1) and in August 1995 (EEP3) or will be disseminated in the framework of other regional training workshops, to be held in 1995 and 1996 in the framework of each of the EEP sub-activities: EEP2 in January 1996 and EEP1 (second workshop) in June 1996.

2. PROJECT ORGANIZATION

The Energy Environmental Planning Core Consultant Group is based mainly on the EPCCT/AIT, with the co-operation of experts from the Institute of Energy Policy and Economics (IEPE — France) and from Enerdata S.A. (France), and with the technical support of the Natural Resources Section of the Environment and Natural Resources Management Division (NRS/ENRMD) of ESCAP.

EPCCT is responsible for the implementation of the three sub-activities [1], in consultation with ESCAP and with the in-country study teams for the overall approach; it is also responsible for the methodologies and procedures to be used in the framework of the project; it ensures assistance on methodological and implementation aspects in each of the activities; and it is in charge of the dissemination and follow-up of the methodologies and tools transferred to the in-country study teams through regional training workshops and also through on-the-job training and through technical and advisory missions for the duration of the project. EPCCT will prepare the synthesis reports of all activities, which will be presented in the final regional workshops of each sub-activity together with the in-country studies prepared by the in-country teams. EPCCT will also edit and publish the reports on methodological developments, software user manuals, technical manuals and final reports (synthesis reports); in addition, EPCCT will co-operate with the in-country teams to edit and publish their national reports.

The in-country study teams participating in the various sub-activities are from the following countries: Cambodia, Democratic People's Republic of Korea, India, Indonesia, Islamic Republic of Iran, Laos, Malaysia, Mongolia, Nepal, Pakistan, Philippines, China, Republic of Korea, Singapore, Sri Lanka, Thailand, Viet Nam.

The in-country study teams are composed of several energy-environmental planners and researchers from governmental agencies and also from universities or research centres in order to ensure the sustainability of these activities and the continuity for future methodological developments and for in-country training purposes; the activities of these teams will be co-ordinated by an in-country team leader (or PACE-E/EEP sub-focal point).

The in-country teams are responsible for conducting the in-country studies in their respective countries, including data identification and collection, application of methodology and techniques, as well as for co-ordination of activities with PACE-E national focal points, with the central consultant (EPCCT) and with the working group on EEP; they will also have to deliver final study results and reports, and participate in dissemination activities within their own countries. The teams will be represented by their most specialized team members on the occasion of training workshops; the team leaders will participate in co-ordination meetings and in regional workshops to present the results of the study. The in-country team leaders or the EEP sub-focal points report to the central consultant for overall technical and administrative support.

All project workshops and meetings are initiated and directed by the central consultant, with the assistance of EPCCT, ESCAP and the working group on EEP. For dissemination activities, which have to continue throughout the project, the central consultant will co-ordinate with ESCAP, the PACE-E national EEP sub-focal points and the respective national agencies to identify the most qualified participants and to work out follow-up recommendations. The central consultant will report to ESCAP on all project related matters.

3. METHODOLOGICAL APPROACH

3.1. Energy-environmental situation in Asia

Adequate supply of safe, affordable energy is a basic need. Without it, economic development and elimination of poverty are inconceivable. However, all forms of energy that are widely available at an acceptable cost impose environmental penalties. Thus, an important challenge for each country and for the world as a whole is to manage the trade-off between adequate and affordable energy supplies and environmental quality. This trade-off must be managed with consideration of the present and future generations.

'Sustainable development', which is defined as a process of ensuring that current consumption of energy is not financed by incurring economic debts that must be paid by future generations, is a crucial concept for effectively addressing the energy-environment interface. In the energy context, this means that natural resources must be used in ways that do not create ecological debts by over-exploiting the carrying and productive capacity of the Earth. While recognizing that sustainable development is now widely embraced as a key societal goal, it is clear that specification of sustainable policies for the energy sector is a complex task that poses serious dilemmas for many countries in Asia. In particular, the pressure on countries to reconcile economic development imperatives with effective and efficient environmental management practices is likely to remain a source of potential tension in both domestic and international policy making arenas for some time to come.

All of the developing countries in Asia have strained to achieve a balance between energy production/energy imports and the desired energy consumption. Because the countries are developing rapidly and energy production capacity must be added quickly, emphasis has been placed on minimizing capital costs, with relatively little concern for environmental consequences.

Most countries have to import some or all basic energy sources, crowding out other goods and services whose import is essential for development. Other countries have an undeveloped energy export capacity that could potentially be used to finance pressing development needs. The oil price shocks of 1973–1974, 1979–1980 and 1990 reinforced the realization of the vulnerability of oil importing nations. They also increased the attractiveness of natural gas and coal as substitutes for petroleum. Thus, basic economics, the realization of vulnerability to foreign supply disruptions, and increased sophistication have modified the energy strategy from one that is preoccupied with capacity expansion and importation to one that places more emphasis on efficiency of use and on development of domestic energy resources.

Rapid consumption growth and volatile petroleum supply have increased global and local awareness of the environmental consequences of energy production and consumption. Problems of sustainable growth in connection with energy-environmental problems have not been priorities in developing countries struggling to simply meet the demand in a way that requires the least monetary outlay, particularly for foreign exchange. Increasingly, however, countries are feeling the pressure from multilateral lenders and donor countries to pay more attention to the environment and to sustainable growth in their energy development programmes. Also, since many of these countries have become more prosperous, their citizens are becoming less willing to sacrifice environmental quality (including public health) for cheap energy. As a consequence, the developing countries of Asia are seeking technical and scientific information, as well as state-of-the-art methodologies and tools for energy–environmental analysis, to help them make informed decisions in the area of energy–environmental policy.

The present project, EEP, is a programme element of a larger UNDP sponsored programme, PACE-E, which finances a variety of interventions across the energy–environmental sector. The project will finance the costs of 20 country studies aimed at providing current data on energy demand and pricing, which are critical to the development of national policies for conservation and environmental protection. The country studies constitute the practical application of the skills imparted in the training seminars and thus are critical, not only as the key output for policy developments but also as a means for institutionalizing a self-reliant, sustainable analytical capacity in the participating countries.

3.2. Programme justification

3.2.1. Problems to be addressed

The UNDP sponsored Regional Energy Development Programme (REDP), which was in operation between 1981 and 1991, had as its overall objective assisting the developing countries of the Asia-Pacific region to adapt to the volatility of the energy market, chiefly in petroleum. The combined interventions of this project, in which 20 countries of the region participated, are considered to have largely met the development objective of increasing the overall supply of energy in the countries, as well as greatly strengthening (and, in some cases, creating) the energy planning capability within the countries.

However, a major area of unfinished business to be addressed by PACE-E, the successor to REDP, is the 'environmental connection' of the whole problem of increasing the availability of energy. In this area, issues such as demand estimation, fuel conservation and substitution, and environmental impact analysis are of paramount concern, and place new and incremental demands upon a nation's analytical and planning capability. At present, the planning capabilities of the countries participating in PACE-E are unequal to the challenge of providing the kind of sophisticated analysis and scenario simulation required to inform policy makers in the energy-environmental sector. Thus, the nations of the regions, all of whom must contemplate major investments in energy producing infrastructure over the next decade, have critical uncertainties and gaps in their informations, which may produce environmentally undesirable choices.

It should also be emphasized that the current planning capability of the countries (which, to some degree, mirrors their level of economic development) is highly uneven. Countries such as China, the Republic of Korea and Thailand have made tremendous progress in developing a planning capability under REDP and other United Nations programmes during the last ten years. In contrast, countries such as Laos have begun to develop effective databases for some energy subsectors (e.g. electricity), but have yet to produce reliable data for other sectors (sectoral energy demand). This variability among the participating countries creates additional challenges to the implementors of the project, who must adapt their technology and training materials accordingly. It also underscores the importance of the *in-country studies*, both as a planning instrument and as a way of finding out which countries have truly grasped the methodologies involved in advanced energy planning and which countries will require further training and technical assistance.

In this regard, one final remark needs to be made regarding the importance of 'enrolling' as many countries as possible in the overall regional initiative. Clearly, in the energy–environmental sector more than in any other sector, what counts is the sum of all efforts made regarding energy conservation and reduction of pollution, and not isolated initiatives of countries.

3.2.2. *Expected end of programme situation*

By the end of the four-year project period, the analytical capability of at least ten countries of the region will have been upgraded in order to take into account: (1) sectoral energy use (demand side analysis) and scenario building to evaluate energy conservation and fuel switching potentials, and (2) environmental concerns when developing plans and policies for the energy sector (supply and demand side analysis). Specific skills and technologies transferred will include: (a) environmental impact analysis of increased demand for energy from the industrial, transport, services, agricultural and household sectors, and also from the energy sectors; (b) evaluation of the benefits and costs of different scenarios of energy conservation; and (c) improvement of the energy–environmental database to support other sub-activities.

The principal outputs of the project will be the twenty country studies, the quality of which will serve as the primary indicator of the extent to which skills have been successfully transferred. Ten of these studies will focus on demand side management, efficiency and conservation issues, and ten will deal with the integration of environmental considerations into energy policy and planning of the overall energy system.

3.2.3. *The beneficiaries*

Inasmuch as all segments of society use energy and are impacted by the environment, all individuals can be regarded as beneficiaries of the project's activities. However, the direct recipients of this programme are the policy makers, administrators and technicians dealing with energy planning and environmental concerns. In addition, representatives from the private sector and from universities are included in the training activities of the programme to permit a future follow-up of the activities, as well as to create the capacity to carry out further training in the countries and therefore to ensure the sustainability of the project.

3.2.4. *Programme strategy and institutional arrangements*

The ESCAP Secretariat, as the co-ordinator of the working group on EEP, is the executing agency of this project, while AIT is the implementing agency. Three sub-components are being developed within the framework of the programme. To ensure continuity with past interventions under REDP, the project selected a methodological approach and employed a team (the EPCCT/AIT) that relies upon experts from the School of Environment, Resources and Development at AIT and from other international institutions to provide training and technical assistance to the countries.

In the first sub-component (EEP1), the EPCCT/AIT prepared a guidebook on energy surveys [2], which was disseminated to the participating Asian countries on the occasion of the training workshops [3]. A synthesis of the actual status of energy surveys, energy statistics and sectoral energy data was also prepared by EPCCT in the framework of this activity [4-6]. In addition, specific sectoral energy surveys will be prepared together with the participants on the occasion of the second training workshop to be held in the framework of this activity.

In the second sub-component (EEP2), EPCCT is reviewing past applications of methodologies, models and existing databases, and will eventually modify them to render them suitable for the evaluation of energy saving (conservation) and fuel switching potentials under various scenarios [5-11]. One scenario being studied will involve demand side management (DSM) options, improved efficiency in end use and fuel switching options resulting in lowered demand for energy; a consequence of this scenario will be an improvement of the environmental situation. The results of this review could be used to design the regional training workshop required for activities (in-country studies) to be implemented between 1996 and 1997. In addition, the results obtained in the framework of the EEP4 sub-activities, executed and implemented by APDC/APENPLAN, will be an important input for this sub-activity.

As a follow-up to the regional training workshop, approximately ten in-country teams will be established in the last quarter of 1995 via activities carried out under the aegis of PACE-E to undertake the in-country studies. The advisory missions will assist each in-country team at the beginning, the middle and the end of the in-country studies. The reports from the in-country studies will be synthesized by the central consultant's team and by the PACE-E secretariat in the second and third quarters of 1997, to obtain a regional overview of the likely conservation and fuel switching potentials and strategies as well as of their expected impacts on the environment. The synthesis report will serve as the principal resource document for a regional workshop, scheduled for the first quarter of 1998. The findings, conclusions and recommendations of the workshop will be published also in the first quarter of 1998.

The same strategy will be employed for the third sub-component (EEP3): integration of environmental considerations into energy planning and policy analysis. In this case, AIT undertook a review of the existing methodologies and procedures for incorporating environmental factors into energy planning. The emphasis was on identifying an appropriate energy analysis methodology and tool capable of integrating scenarios that cover the overall energy system, as well as on determining the structure of the supply system, given various demand scenarios, relating these to environmental impacts and rendering the structure 'user friendly' in the context of the participating countries [12–18]. Upon completion of the review (by the end of June 1995), AIT presented its findings and recommendations at a regional training workshop, held in August 1995. During this workshop, the participants were trained for the application of the selected methodology as well as of the 'user friendly' software (EFOM-ENV); also, an in-country study framework was presented and discussed with the participants.

Following the workshop, AIT energy planning specialists are organizing, together with the participants from the countries, approximately ten in-country studies on the interaction between the energy systems and the environment. AIT energy planning specialists, who are conversant with the methodology, will assist the in-country teams by conducting three advisory missions to each country: to initiate the study, to follow up the progress and to evaluate the quality of the country reports. Finally, the consultants will prepare a synthesis report, aggregating the results contained in the in-country reports; they will then present these results at a regional seminar attended by policy makers from the ten participating countries.

A key aspect of the project strategy is the 'bottom-up' approach in which technical and administrative officials, charged with formulating national energy sector plans and policies, are made responsible for the execution of the project activities, e.g. the in-country studies. The participation of research and/or academic institutions of the participating countries is an important element to secure the technical support and the follow-up of the in-country teams.

3.3. Development objective

The development objective of PACE-E, of which the present study is only one component, is to enable Asian countries to make progress towards the achievement of balanced, sustainable economic growth based upon an environmentally responsible production and use of energy. As such, the project should be seen as building upon and extending the development principles expounded in the Brundtland Commission Report and strongly endorsed at the conference in Rio de Janeiro.

The project also embodies a strong element of regionality. Its geographical scope extends over most of Asia. Its organizational structure is based upon the integration of inputs from approximately twenty countries of the region. It seeks to enhance regional capabilities in the various planning, management and technical fields that will enable individual nations to develop and utilize energy resources in a way that is compatible with the objective of sustainable development.

3.4. Outputs

The expected main outputs of this sub-activity are:

(a) Training workshops and published methodological guidelines, together with case study applications, which could be used as the basis for new training courses with a primary environmental focus.

(b) Training programmes on energy cost analysis and pricing, to share experiences on whether subsidized energy is achieving its objectives, which alternatives to energy subsidies might achieve the same goals, and how to analyse energy costs and to set prices in such a way that resource depletion and environmental damage are accurately taken into account.

(c) A combination of training and review seminars for senior energy and environmental specialists from the Governments of the region, specifically directed towards identification of current institutional constraints and shortcomings, coupled with the design of model institutional structures through which energy-environmental concerns may be more actively addressed. These model structures will be promoted by providing guidelines to be circulated in countries in the region.

(d) New training programmes in energy–environmental database development, supported by the preparation of appropriate training materials. In addition, it may be useful to consider preparation of technical guidelines for the development of energy–environmental databases within an agreed common framework for application in developing Asian countries.

(e) Publication of methodological, training, users' and technical manuals, as well as guidebooks covering all aspects of the three sub-activities EEP1, EEP2 and EEP3 [1–18].

4. CONCLUDING REMARKS

The various issues addressed by the EEP1, EEP2 and EEP3 activities are of huge importance in Asian countries, particularly in the actual context of economic and energy development of these countries. It is important to provide the energy planners, working in governmental and official institutions, with the knowledge and the tools that will help them to analyse their country's situation and to make wise decisions for the future, integrating economic growth, sound environmental concerns and efficient energy development.

As mentioned above, the main objective of EPCCT/AIT in the framework of these EEP sub-activities is to give to the decision makers the information (data), the knowledge (methodological approach of the energy–environmental problems) and the tools (models) that will help them in their day to day planning and policy activities. ESCAP and EPCCT/AIT have been working in this direction for the last ten years, developing new methodological approaches to the energy-environmental problems in Asian countries, designing and developing new tools to carry out planning activities, and collecting, checking and organizing energy-environmental data to enable the Asian countries to use more effective energy-environmental planning tools. During all these years, the activities of ESCAP and EPCCT/AIT have been focused on assisting the Asian countries in strengthening their capabilities to carry out their own energy planning and policy activities. Great importance was attached to the in-country studies, once the methodologies and tools had been transferred. Additional on-the-job training will be carried out, i.e. officials and planners will receive their professional training in short time periods as part of their professional activities and in the framework of the implementation of their in-country studies. The in-country energy planners, with the support of the main consultant team, will try, by themselves, to develop an integral energy-environmental planning activity, passing through all the phases of this process, from data collection to the production of a final report, and recommending the policy options to the decision makers. The final objective of this activity is the integration of the knowledge and skills acquired during the project into the day to day planning activities; this will in fact represent the long term effect sought by this activity.

Another important facet of the project is the incorporation (since the beginning of the project) of representatives from universities and research centres in the training activities as well as in the in-country study teams. Their involvement is an important element of the project because it will permit the reproducibility of training activities in the future, which is needed at the national level; it will also enable further development of methodologies and software, in co-operation with the official national planning agencies, thus ensuring the long term sustainability sought by the project.

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THE ENVIRONMENTAL MANUAL FOR POWER DEVELOPMENT
*Status and results from case studies in the Philippines, Poland and Morocco**

T.C. HERBERG
Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH,
Eschborn

U.R. FRITSCHE
ÖKO-Institut e.V. (Institute for Applied Ecology),
Darmstadt

Germany

Abstract

THE ENVIRONMENTAL MANUAL FOR POWER DEVELOPMENT: STATUS AND RESULTS FROM CASE STUDIES IN THE PHILIPPINES, POLAND AND MOROCCO.

The Environmental Manual for Power Development (EM) is a multiyear and multi-donor project sponsored by a group of bilateral and multilateral development agencies and is co-ordinated by the World Bank. The EM is a Windows based computerized tool for the analysis of the environmental impacts of energy (mainly electricity) systems and of the cost trade-offs associated with project alternatives (e.g. low sulphur fuel, flue-gas desulphurization, demand side management (DSM), cogeneration, renewables). The EM uses the comprehensive life cycle approach to determine environmental impacts (from 'cradle to grave'). The EM database offers a broad variety of generic (prototypical) information on energy systems, including costs, efficiency and environmental impacts. It covers conventional fossil fuel power plants, boilers and their supporting infrastructure (e.g. mining, refinery, transport), transmission and distribution systems, renewable energies (hydropower, photovoltaic power, biomass, wind, etc.), and cogeneration and DSM technologies. Furthermore, emission control technologies are included. The EM can be used for a wide range of applications — from 'early screening' of energy projects under consideration, and energy/environmental planning of utilities and countries, to cost impact analysis of setting different environmental standards. During its development, the EM was tested in real-world applications to demonstrate its usability; these case studies included both database adaptations to the countries and application of the model to support the decision making process on energy systems. Results from the Philippines, Poland and Morocco are presented, and future activities are addressed.

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* A project co-ordinated by the World Bank and jointly sponsored by the Governments of Germany, Netherlands, Switzerland and the United Kingdom.

1. ORIGINAL IDEA, STARTING POINT

In their efforts to support human well-being and economic growth, developing countries throughout the world face a daunting challenge: they have to bring about a rapid expansion of their energy infrastructures at huge costs.

- The International Energy Agency estimates a growth in electricity demand in East Asia for the period 1990–2000 at a rate of about 6.1% p.a. and expects burning of coal to increase by 12.0% p.a. [1].
- The present shortfall in installed generation capacity in India and China is about 18 000 MW in each country [2].
- For China, a growth in electricity demand of 6% p.a. up to the year 2000 is expected and the gross generating capacity will have to increase by an additional 100 GW [3].
- For the Philippines, a growth in energy demand at a rate of 9.4% p.a. is expected, to be covered by an additional 19 000 MW of generating capacity up to the year 2000. The estimated respective collateral investments in infrastructure, such as gas fields and pipelines, transmission lines, and coal handling and processing installations, will reach US $ 69 000 million for the 1994–2010 energy plan [2]. The estimated increase in CO_2 emissions will reach 100%.

Energy projects and their supporting systems — from fuel extraction and storage to distribution — can and will be major contributors to local, regional and global environmental pollution and degradation. Therefore, in order to minimize the continuously growing environmental effects, careful attention has to be given to the diverse environmental impacts of different alternative energy supplies and, at the same time, economic parameters have to be taken into consideration.

Because of the wide range of energy options — from the use of fossil fuels to the implementation of demand side management (DSM) measures — and their varying environmental effects and associated costs, there is a need for a compact, easy to use, accurate and up-to-date evaluation tool that can be used by Government agents, energy planners, environmental engineers, regulatory bodies, lending agencies, private investors and public interest groups.

It is crucial to make use of the best available information, analyses and instruments in order to develop a transparent basis and framework for decision making. However, in 1990, there was no such instrument. Different institutions were working on diverse databases, but all seemed to cover only parts of the expected technology data.

A group of bilateral and multilateral co-operation agencies, co-ordinated by the World Bank, came together in 1990 to determine the specifications for such an instrument and to find the appropriate financing. Finally, in autumn 1992, the group began to develop a computerized tool that combines both a suitable set of methodologies to compare alternatives and an appropriate expandable database. Under the management of the World Bank, the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) started the development of the model, with the scientific support of the ÖKO-Institut (Institute for Applied Ecology, Darmstadt). The GTZ operates with financial support of the German Government and its work is directly co-ordinated with the Kreditanstalt für Wiederaufbau (Frankfurt) — a bank strongly involved in infrastructure financing. Two other institutions supported the work, the Overseas Development Administration (ODA), London, and the Bundesanstalt für Aussenwirtschaft (BAWI), Bern.

2. QUESTIONS TO WHICH THE ENVIRONMENTAL MANUAL FOR POWER DEVELOPMENT (EM) SHOULD GIVE ANSWERS

The privatization process within the power sector is in progress worldwide. The influence that governmental institutions have on the environmental effects of the power sector becomes increasingly indirect. The role of Governments and their institutions therefore consists, to a small extent, of accurate expansion planning, but mainly of controlling that the power sector secures the expected services to the public at acceptable costs for the economy as a whole as well as for individual users. This requires strategic, environmentally oriented, indicative planning and instruments that allow alternative strategies to be analysed with respect to their micro- and macro-economic and environmental aspects. Damages caused by hazardous emissions, generated by a privately run sector, but which are damages to the public in general, have to be estimated and transformed into economic units.

The Government, with its regulatory role, has to seek minimization of these economic costs. Information on both the internal energy generation costs and the so-called external cost components should comprise the complete electricity supply system, and the costs must be assigned to their sources. When deciding on energy policies or sector strategies, Governments must know the overall long term environmental effects caused by such decisions, and alternative energy system approaches should be considered. At the same time, regulations impeding private sector involvement in individual plants must be avoided, but environmental or economic necessities should not be sacrificed for the sake of private economic interests.

Therefore, the effects of national standards should be accessible to a regulatory body. It should have a detailed knowledge of the possible savings in external costs and of the expected emission reductions achieved by adaptation measures, as well as of the need for additional investments. This is true not only for the electricity generation side but also for the qualities of the fuel to be used — imported or provided by the transformation subsector.

To support international negotiations, Governments should also know the state of greenhouse gas (GHG) emissions in the power sector, their future development, the sources and the options to reduce them, as well as the necessary investments and the so-called technology.

International lending agencies focus their interest on the technologies to be used, because these should comply with their own economic and environmental standards. These agencies also need to support their partners in developing energy and environmental strategies that minimize economic costs. Therefore, these agencies have to be able to analyse the environmental effects of the technology in question and its numerous alternatives within the overall system development characteristics. Also, the contribution to the greenhouse effect and the environmental effects caused elsewhere by national strategies or investments should be known.

Private investors have to comply with standards at minimum internal costs, thus maximizing their profit. In order to check operational and technical alternatives within their installations or through the use of other fuels, they have to analyse the effects of environmental laws and standards on the operation of the installations in which they invest.

Public interest groups control and advise the political decision makers. They want to estimate the implications of planned investments, not only in terms of the local effects and the expected changes in tariffs caused by changes in generation costs but also in terms of global effects or effects on other population groups.

Requirements for an analytical tool

An analytical tool should:

- be easy to use, flexible and accurate;
- contain a database for developing countries, realistically representing the diverse solutions, including modern technologies as examples for the user;
- offer an adjustable database for individual case studies;
- allow for early screening of options using environmental standards for emissions;
- include life cycle effects in order to realistically represent DSM and, in particular, renewable energy technologies;
- include DSM options as examples;
- include heat and power generation for comparison of cogeneration solutions;
- allow to compare environmental effects and cost effects for individual power plants and for complex electricity generation systems;
- detect emissions generated locally and elsewhere;
- help identify mitigation options;
- allow for trade-off analyses;
- allow emissions to be translated into costs in order to make them comparable, and offer information on cost factors for different environments.

The EM has been elaborated to respond to these requirements.

3. BRIEF DESCRIPTION OF THE EM

The EM is a Windows based computerized tool for the inclusion of environmental and cost data into the decision making of power utilities and development banks for energy projects, as well as for sector institutions for strategic energy planning and setting of environmental standards.

The software was developed by the GTZ and the Öko-Institut within an ESMAP project funded by the Governments of Germany, the Netherlands, the United Kingdom and Switzerland and co-ordinated by the World Bank.

The EM software can analyse and compare airborne and GHG emissions, solid wastes and land use, as well as internal and external costs associated with the investment in and operation of all kinds of energy technologies, including their life cycles (upstream fuel cycles and material acquisition). It can compare power plant emissions with predefined environmental standards and indicate the need for adaptation.

The EM has a database for generic energy technologies and covers:

- all fossil fuelled electricity generation and heating systems;
- cogenerators;
- renewable energies (for electricity and/or heat);
- energy efficiency (DSM) technologies;
- nuclear power systems;
- data for 'upstream' activities such as mining, fuel benefication and transport;
- data for emission control systems such as flue-gas desulphurization (FGD), electrostatic precipitation and selective catalytic reduction.

The EM can run scenarios to compare not only single power plants or boilers but also complete electricity generation systems.

The EM has a fully interactive on-line help system and an on-line data documentation.

The EM software is available at no cost through the Internet, where also user support can be given via the World Bank's EM User Group.

4. EXAMPLES FOR APPLICATION OF THE EM

The experience described in the following sections covers nationwide applications, regional studies, as well as analyses of individual projects.

4.1. The Philippines

The Philippine case study was part of the development process of the EM. It was an extended, six month, field test that helped to improve the instrument and to

TABLE I. ANALYSED SCENARIOS IN THE PHILIPPINES

No.	Name of scenario	Measures taken	Installed capacity (MW)	Generated energy (GW·h)	Participation of fuels								
					Coal (%)	Bunker-C oil (%)	Diesel (%)	Geo-thermal (%)	Hydro (%)	Gas (%)	DSM (%)	Wind (%)	Bio-mass (%)
A	Base 1993	As is	7 885	26 620	9.23	27.49	23.4	21.3	18.6				
B	Base 2000	As planned	13 795	57 690	31.5	12.69	21.9	12.6	21.3	0			
1	Oil-thermal with FGD	As base 2000	13 795	57 690	31.5		21.9	12.6	21.3	0			
		10 oil-thermal power plants with FGD	2 000	7 318		12.69							
2	Oil-thermal with low S	As base 2000	13 795	57 690	31.5		21.9	12.6	21.3	0			
		10 oil-thermal power plants with bunker-C oil, with S content reduced to 0.9%	2 000	7 318		12.69							
3	Coal with FGD	As base 2000	13 795	57 690		12.69	21.9	12.6	21.3	0			
		22 coal power plants equipped with FGD	3 300	18 160	31.5								

4	Coal with low S fuel	As base 2000	13 795	57 690		12.69	21.9	12.6	21.3	0			
		Coal import from Australia with S content (0.5%)	3 300	18 160	31.5								
5	Gas-CC replacing oil and coal	As base 2000	11 645	57 690	17.2	5.55	11.5	12.6	21.3				
		8 CC gas fired power plants	2 400	18 450						32			
6	DSM replacing oil	As base 2000	13 324	57 690	31.5	11.23	21.9	12.6	21.3	0			
		Lighting (7.5 million CFL)	293	669							1.16		
		Refrigeration (0.5 million refrig.)	12	72							0.12		
		Air conditioning (90 000 air conditioners)	24	96							0.17		
7	Wind replacing oil	As base 2000	13 882	57 690	31.5	12.69	21	12.6	21.3	0	0		
		10 wind parks	87.5	500								0.87	
8	Biomass replacing oil	As base 2000	13 795	57 690	31.5	10.6	21.9	12.6	21.3	0	0	0	
		GT run with gas from biogasification (bagasse)	100	600									1.04

TABLE I (cont.)

No.	Name of scenario	Measures taken	Installed capacity (MW)	Generated energy (GW·h)	Participation of fuels								
					Coal (%)	Bunker-C oil (%)	Diesel (%)	Geo-thermal (%)	Hydro (%)	Gas (%)	DSM (%)	Wind (%)	Bio-mass (%)
9	Gas-CC + DSM + Wind + low-S oil + coal FGD	As base 2000	13 795	57 690									
		Coal gen. reduced by 750 MW	2 550	15 840	27.5								
		Oil–th. gen. reduced by 1000 MW	1 000	5 079		8.804							
		Diesel gen. reduced by 1050 MW	2 750	8 831			15.3						
		New gas power plant	900	6 300						10.9			
		DSM as in scenario 6	329	837							1.45		
		Wind as in scenario 7	87.5	500								0.87	
		Biomass as in scenario 8	100	600									1.04
		Hydro unchanged	2 550	7 260				12.6					
		Geothermal unchanged	2 145	12 260					21.3				

adapt it to user needs. It was carried out together with the US Department of Energy (DoE).

4.1.1. Questions to be answered

The following questions posed by the DoE were the basis for the application of the EM:

(a) The interest first concentrated on getting to know the present situation (1993) in the power sector:
   — What are the environmental effects and which are the main contributors in the power sector today?
   — How does the performance of these contributors relate to national and international environmental standards?
   — What are the estimates for the external costs caused by the emissions?

(b) The next step was to look into the future:
   — What will be the expected emissions caused by the expansion plans for the near future (up to the year 2000)?
   — Do the planned installations comply with national and international environmental standards?
   — What are the options to reduce the emissions of the major contributors? What are the effects of these options, what will they cost and who will pay?
   — Will the resulting costs of complying with the standards be acceptable for the utilities (internal costs) and for the country (external costs)?
   — Will the savings in external costs justify the additional investments?

(c) Further questions asked were:
   — What are the measures that can be realized using the instruments the Government has at its disposal?
   — Should natural gas be used for power generation? What would be the effects?
   — What could be the role of renewable energies and what would be the environmental gains?
   — Do present and planned DSM measures really have the expected environmental and cost effects?

4.1.2. Application of the EM

The above questions could be answered. The following scenarios, describing alternative supply options, were analysed (see also Table I);

(a) 'As-is' description of the present supply system (1993);

(b) 'As-planned' supply system for the year 2000;

(c) Adaptations to the scenario for the year 2000:
   - Impacts of FGD at major power plants versus reduction of the sulphur content in refineries (affecting a large number of consumers);
   - Refurbishing 22 coal power plants for FGD versus the use of imported low-sulphur coal;
   - Effects of the replacement of heavy oil, diesel and coal by gas fired combined cycle power plants using the natural gas resources from gas fields currently being under development;
   - Effects of ongoing DSM programmes;
   - Effects of improved biomass use in the sugar industry;
   - Impacts of possible wind energy developments.

4.1.3. Some results

The situation in 1993 shows very high specific emissions (especially of CO_2) from thermal power plants. Coal and oil fired plants operate at too low efficiencies and with fuels of very high sulphur content. In many cases, operating plants do not meet the national emission standards.

Although it is planned that more efficient modern power plants should compose the generation system for the year 2000, the environmental situation will worsen in absolute and also in relative terms. The environmental burden will increase because an important switch from the use of oil to the use of domestic coal with high sulphur content is envisaged. The total SO_2 emissions are expected to double by the year 2000 for the planned system expansion, and specific SO_2 emissions will still increase by 2%.

Altogether, the analysed measures to adapt the present expansion plans for the year 2000 seem to be able to significantly cut down the generation and environmental costs. The overall generation (internal) cost could be reduced by some 9% from approximately US $70/MW·h to US $65/MW·h, even though the costs for coal based generation would increase by approximately 3.5%. The scenarios analysed would allow the SO_2 emissions to be reduced by over 70%, which represent for the whole system some 380.000 tonnes per year.

To make the specific emissions of the diverse scenarios more comparable, the option of monetizing them has been used. Many studies are being elaborated internationally to determine the damages caused by the diverse emissions, but the resulting values are insecure and very much in dispute. The analyses included in the EM are therefore based on relatively low monetization factors. They describe the mitigation costs calculated for a 30% reduction of emissions in OECD countries and therefore reflect the willingness to pay for emission reductions. The overall external costs representing all emissions would be reduced by the proposed changes in the expansion plans by nearly 50%.

Calculation of changes in internal and external costs and their relation allowed the individual measures analysed to be given priority. It was possible to find several 'win-win' solutions that allowed not only to reduce emissions but also to save generation (internal) costs. The DSM measures were given first priority, followed by the improved use of biomass in the sugar industry, but both had a relatively small absolute impact. A real step 'forward' would be the replacement of existing and planned oil and coal power plants by natural gas fired combined cycle power plants. It is interesting that the resulting priorities in the sequence of adaptation steps did not vary significantly when the applied cost factors were changed.

4.1.4. Application experience

For the description of the present electricity sector and the supporting infrastructure it was necessary to handle about 4000 pieces of data. To support this effort, the EM not only offered the database structure to store the data but also helped to immediately interlink each of the represented plants, fuels, transport systems, mines, etc. to form a power generation system that covers a specific demand for power and energy. For the description of additional future scenarios it is only necessary to add up the relative changes.

The data were brought together from diverse sources, each of them storing the data in the form and with the content that best suit their specific needs. Demand data as well as estimates for their future development were obtained from the DoE and the National Power Corporation (NPC). Data on power plants came from NPC, private owners, regional utilities and the industry. Data on fuel composition, origins and transformation were obtained from the Philippine National Oil Corporation, the geothermal energy utility, the petroleum companies, the sugar industry and others. Prices differed largely from source to source. Data on petroleum conversion were obtained from the subsectoral entities. Transport data also had different sources. In most cases the data were not complete; they were usually in different units and from different years and thus had to be transformed or completed. Information from other countries had to be used. In several cases, the information from the various institutions was not consistent. The EM offered the possibility to check the consistency of the data, to easily adapt them and to ensure that changes are taken into consideration at every affected point in the system.

The *generic database* helped to bring together technology and environmental data if they were missing. When searching for data on new power plants or on system components, the EM allows technically viable solutions to be rapidly filtered out of the generic database, and fitting solutions to be counter-checked with given environmental standards. The EM offers information on new technologies and experience from other countries for comparison.

Naturally, it has taken some time to bring together such a large set of data and to ensure their consistency. The initial data set, covering some 200 extraction, transport, conversion and generation processes, as well as some 40 fuels, was set up within three months. But, once this basis is established, it is possible not only to quickly analyse the environmental and cost effects of individual power plants as well as those of the whole system, but also to instantly carry out changes to describe new alternatives. The DoE and NPC are currently completing the data in order to have an up-to-date description of the complete system.

The main application experience can be summarized as follows:

- The EM allows not only to store the data for a large number of different processes, fuels, materials, etc., but also to combine them to form 'scenarios' which describe their individual role in a power supply system;
- The EM allows for consistency checks of data and interrelations;
- The EM helps to describe almost any configuration to be analysed;
- Impacts of adaptations can be analysed instantly;
- Adaptations to alternative scenarios can be compared rapidly to find the most effective configuration fitting under a given portfolio;
- In the case of missing data on new technologies, exhaust filters or other emission control technologies, the database gives data on almost any process looked for;
- On the basis of cost factors that can be adapted by the user, emissions of any kind can be monetized to become comparable.
- Trade-off analyses are instantly offered by the EM.

4.2. Poland

One of the most pleasant and most popular holiday resorts in Poland, Zakopane, suffers from extreme air pollution, especially from the SO_2 loads in the atmosphere, caused by the thousands of individual heating systems, most of which are burning coal. The local geothermal potentials are being studied and developed.

4.2.1. Questions to be answered

As in the case of the Philippines, it was first necessary to describe and analyse the present environmental and cost situation, characterized by the individual heat supply, and then to determine and analyse viable supply options and their combinations, making use of the geothermal potential and a modern district heating system. These options were to be compared with conventional gas fired options, such as the use of boilers or combined heat and electricity generation systems. In the latter case it was of special interest to calculate the emissions avoided by replacing electricity generation in the national grid. The possible contribution to GHG abatement should be shown.

4.2.2. Application of the EM

After adaptation of the database, four scenarios (combinations of supply processes) were designed for the delivery of heating services to 15 000 buildings in Zakopane and some surrounding villages.

(1) Simulation of the existing individual heat supply, including some 2300 heating systems currently fired by wood, coal, coke, liquefied petroleum gas and electricity.
(2) Description of the proposed district heating system together with a geothermal plant for which data could be taken from an ongoing pilot project and a pre-appraisal study.
(3) Representation of a cogeneration power plant (natural gas fired gas turbine with waste heat recovery boiler) which sells the electricity into the grid.
(4) Representation of the same plant as under (3), but using gas prices similar to those in western Europe, to indicate the sensitivity of the results to the gas price.

4.2.3. Some results

Under the present price conditions for natural gas, it could be shown that only the geothermal option appears to be a 'win-win' solution, cutting down supply costs to one half and significantly reducing most emissions (SO_2 by 30%, NO_x by 90%, particulates by 95% and GHG by 75%). This impressing result would be even improved by the cogeneration solution, which could become economically very interesting if gas prices dropped to the current western European level. The cost for the gas fired combined cycle option would be similar to that for the geothermal option, but the emission reductions could be much larger, since cogeneration of electricity replaces production and avoids the related emissions elsewhere. Not only

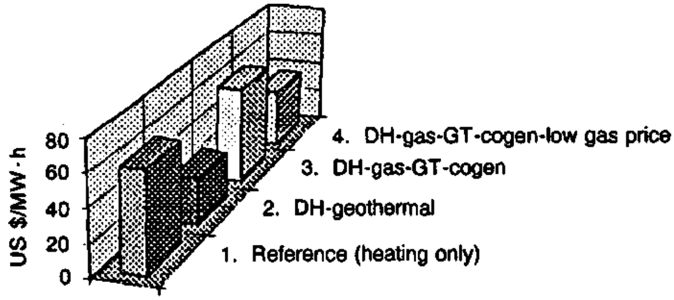

FIG. 1. Poland (Zakopane): Estimated specific generation costs for heat supply.

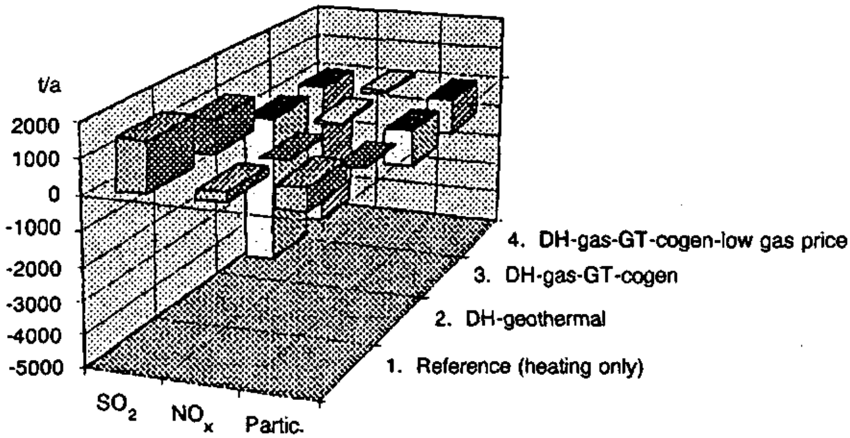

FIG. 2. Poland (Zakopane): Pollutant emissions of supply alternatives.

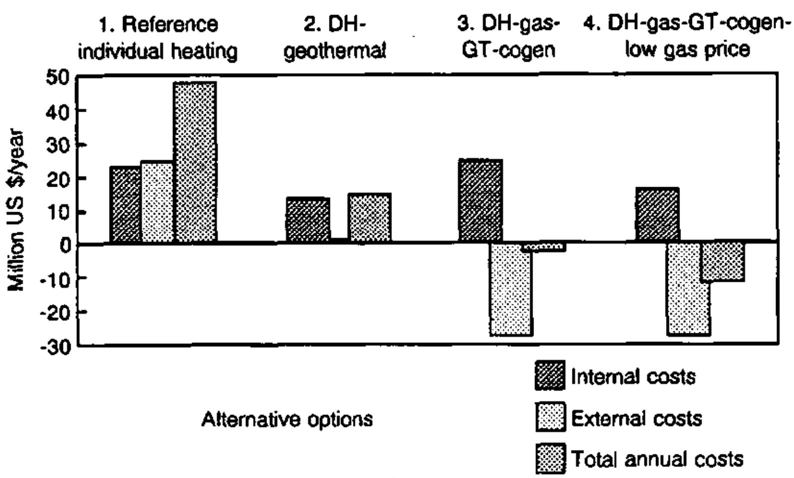

FIG. 3. Poland (Zakopane): Internal and external costs (results of the EM scenario calculation).

would the SO_2 emissions be cut down to zero but there would also be a bonus due to the replaced electricity generation in power plants. The same is valid for GHG emissions. Only the NO_x emissions would increase relative to those in the geothermal option, but they would drop to one third of that in the present supply system (see also Figs 1–5).

4.2.4. Application experience

The complete analysis was carried out in two days. Data on the Russian gas supply system (network, compressors, power plants, etc.) could be taken from the generic database of the EM. The same was true for the characteristics of individual furnaces and the fuels used, for modern combined cycle and geothermal power plants and the replaced generation mix in Poland, for which the EM offered a large variety of data for direct use or comparison with local data.

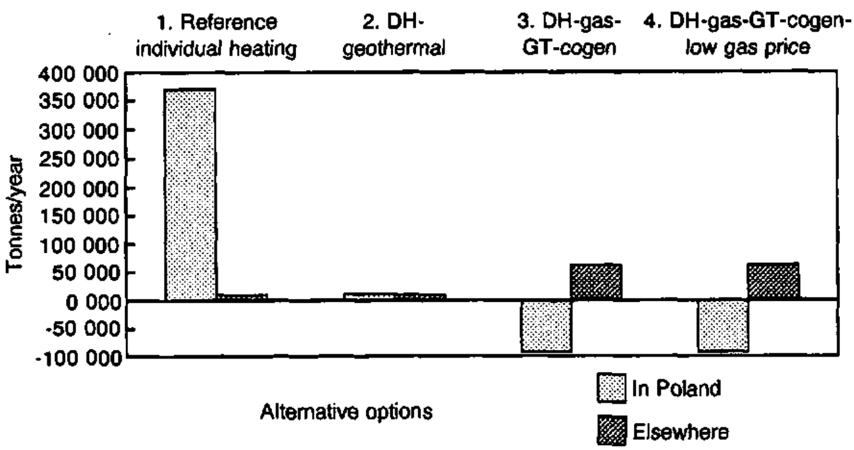

FIG. 4. Poland (Zakopane): GHG emissions of different supply alternatives (results of the EM scenario calculation).

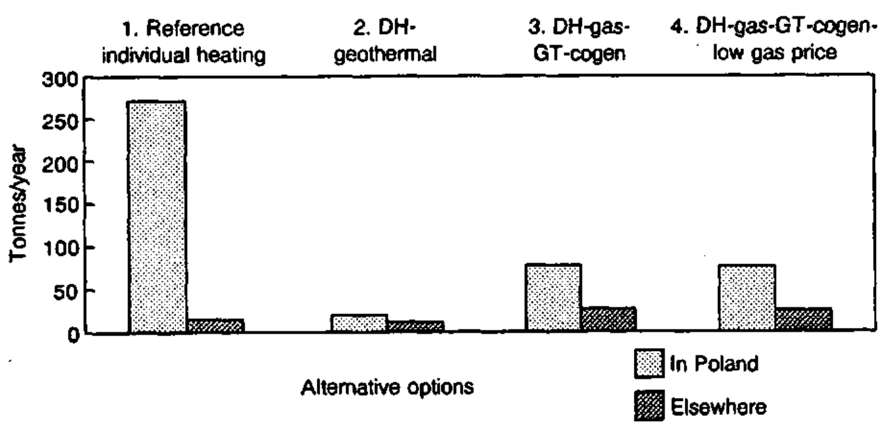

FIG. 5. Poland (Zakopane): Local NO_x emissions and effects of emissions outside the study area (results of the EM scenario calculation).

The most important feature of the EM in this case was the possibility of combining electricity and heat generation in one scenario, allowing for immediate calculation of emission and cost bonuses for the substitution of power generation in other plants.

A specific feature of the EM also allows 'local' emissions (pollutants emitted in the analysed area) to be separated from pollutants emitted outside the analysed region. This feature helped to detect emissions that were of particular interest for the study area of Zakopane, namely reduced emissions in the Polish power industry in other areas, as well as GHG emissions caused, for example, in Russia by increased use of natural gas.

4.3. Morocco

The Moroccan case was different. The application of the EM was to support the ongoing process of national standard setting for large fossil fired combustion plants. The EM was introduced to the National Power Company and the Ministry for the Environment.

4.3.1. Questions to be answered

The questions posed by the utility concentrated on the consequences of future regulations on the operation costs; the possibilities of keeping the currently operating plants and of sticking to the plant additions as planned; the effects on the present fuel supply conditions and the effects of the discussed standards on future capital needs. In view of the present political efforts to attract private investors to the power sector, it was feared that there might be negative impacts.

Apart from the above points, the Ministry for the Environment also needed to compare its own rules with those of other countries; it needed to check the utility's calculations and especially to analyse alternative long term strategies which are not part of the present expansion plans of the utility but which could have positive environmental effects at acceptable economic conditions.

4.3.2. Application of the EM

As in the other cases, it was necessary to first describe the present supply situation. Data for some 30 power plants were adapted on the basis of existing study results from the national power utility. The currently discussed emission standards for existing and new power plants were entered into the database. In a second step the situation expected for the year 2005 was described, taking into account the present expansion plans.

Seven different scenarios were formulated: a reference base case for 1992; a case for the same year but introducing solar and wind power; and another case for

1992 to see the influence of adapting the present system to the envisaged standards. The other four scenarios included the expansion plans for the year 2005 as a base case, and various adaptations to comply with the standards.

An initial comparison with the standards showed those power plants that would not comply with them. The options currently studied cover adaptations of these power plants by changing the processes, adding emission control technologies or even taking older plants out of service. These options give an impression of the changes necessary to comply with the standards, the additional investments involved, the resulting overall generation costs and possibly necessary tariff increases, the emission reductions achieved, etc.

Data adaptation is still continuing. The National Power Company is verifying the data used in the first run of the analysis. The Ministry for the Environment is testing alternative regulations to compare the achievable environmental benefits and the related economic implications. A workshop is planned, which will carry out additional analyses on the basis of these new data and discuss the results on a political level.

4.3.3. Some results

It is remarkable to see the influence of the planned technology change for the year 2005 on the specific SO_2 emissions, which would be cut down to 25%. This influence is such that, even though the generated energy will increase by a factor of three, the emissions will be reduced also in absolute terms. Unfortunately, this is not true for NO_x or for CO_2, but the increment of these emissions is less than that of energy generation. The changes are mainly based on the introduction of natural gas as fuel, with a share in electricity generation of 43%. The generation itself will have a much higher efficiency because of the introduction of combined cycle power plants. The hydropower capacity will be doubled and a 30 MW wind park will also contribute to emission reductions. To accompany this change, the share of coal in electricity generation will also be reduced to approximately 9.5%. The generation costs should be reduced from approximately US \$73/MW·h to US \$52/MW·h.

However, a check of compliance with the given standards showed that important adaptations to the individual plants still have to be considered. The existing coal plants were equipped with control technologies to reduce SO_2 emissions (to 2000 mg/Nm^3) and particulate emissions (to 150 mg/Nm^3) according to the relevant rules of the standards. The same was done for the existing oil fired plants to meet the respective values. Also, all planned new power plants were adapted by adding the adequate emission control technologies in order to comply with much more severe rules. Thus, the given standards caused a specific reduction of emissions to approximately one third, but, on the other hand, they raised the generation costs by some US \$6/MW·h. This increase in costs represents US \$2 per kg SO_2 reduction or US \$2 per kg NO_x reduction (see Figs 6 to 9). Complying with these stan-

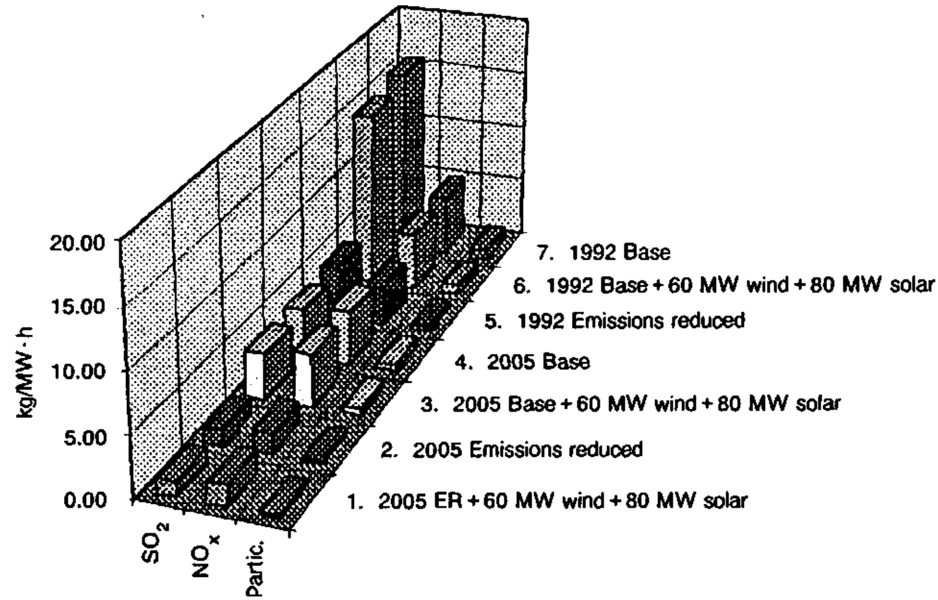

FIG. 6. Morocco: Pollutant emissions for different supply scenarios.

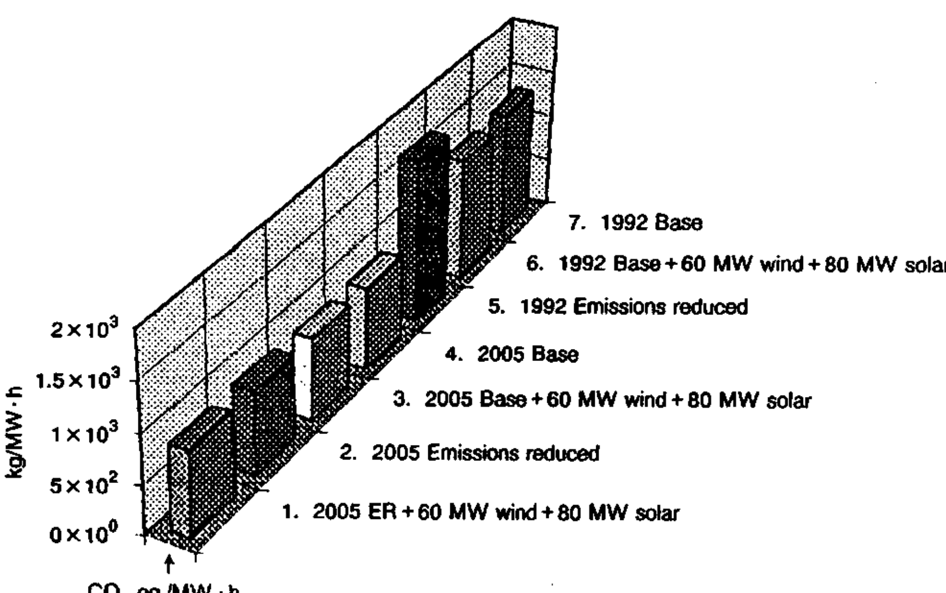

FIG. 7. Morocco: Specific GHG emissions.

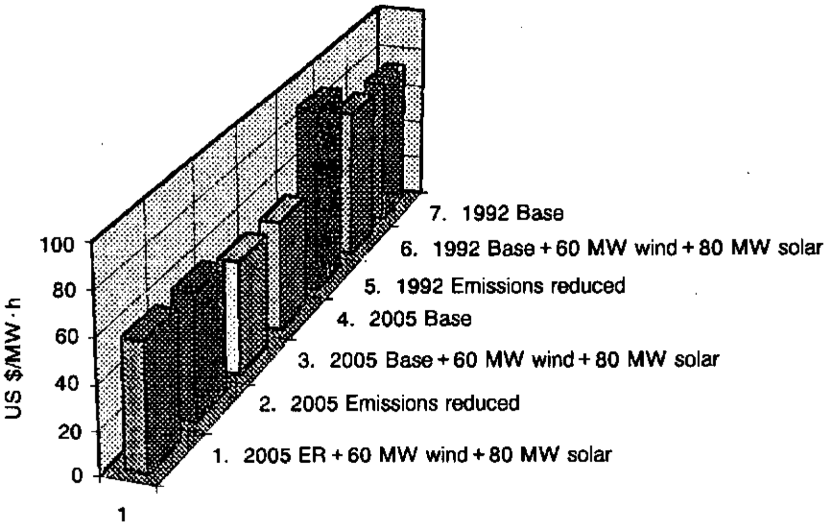

FIG. 8. Morocco: Estimated specific internal power generation costs.

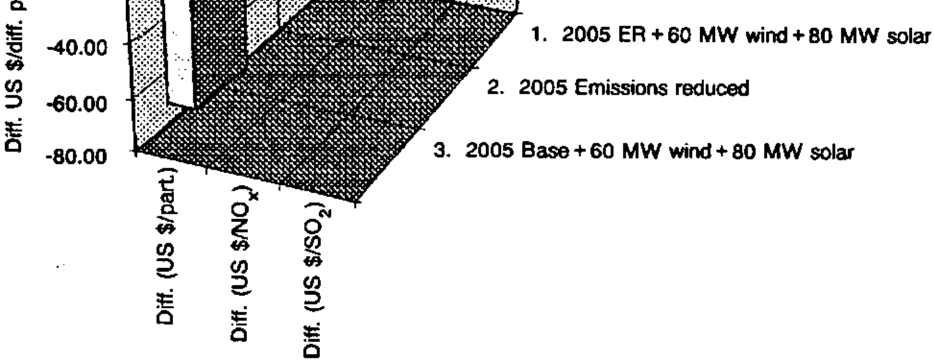

FIG. 9. Morocco: Changes in costs versus changes in emissions relative to the 'as-planned' 2005 scenario (trade-off relative to the 2005 base case).

dards thus results in the need for additional investments adding up to approximately US \$540 million. On the other hand, it will cause internalization of external (societal) costs of the order of US \$520 million per annum.

The influence on costs and emissions of introducing renewable energy systems was also tested. At present, a solar thermal power plant of 60 MW, combined with an oil fired backup boiler, is being discussed, and a 30 MW wind park in the windy north of Morocco is being planned. Their influence in absolute terms is small but still considerable, since these technologies are the only ones that can reduce the greenhouse effect. The SO_2 reduction would also be cheaper than in the conventional case, and would cost approximately US \$1.5 per kg SO_2 reduction; additional generation costs of US \$1 could save some 45 kg of CO_2 equivalents.

4.3.4. Application experience

In a workshop, the EM and the present data were introduced to the Maroccan partners, who are continuing the studies.

The EM automatically analyses all combustion processes to check compliance with specified standards and indicates the rules that are not met.

The EM allows to 'add' emission reduction technologies (from the database), such as the use of filters, taking care of the operation and investment cost increments as well as of their influence on fuel consumption and related emission values. Thus, testing of adaptations is a matter of minutes.

The EM shows the investments needed for adaptation to new standards and estimates the resulting generation costs.

Introducing into the supply system renewable energy technologies such as solar thermal power plants or wind farms to check their environmental and economic relevance is a matter of minutes.

The national process of standard setting is supported by an increased transparency. Alternative standards can also be compared with regulations of other countries.

5. THE NEXT ACTIVITIES

A technical advisory group managed by the World Bank has carried out BETA testing of the EM. An introduction for users and a documentation are integrated into the EM as an on-line help package. An additional on-line help information package is being elaborated by the World Bank and will be introduced in the near future. It will contain guidelines on environmental assessments, on procedures for the environmental review of the World Bank and on industrial pollution regulations, and it will provide good practice examples for technology options. The EM is currently being introduced into the INTERNET for public access.

A first regional introductory seminar and workshop was carried out in the Philippines in early October 1995, with participants from ten Asian countries. This is part of a worldwide dissemination programme carried out under the ESMAP programme of the World Bank and financially supported by bilateral donors.

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THE SEI/UNEP FUEL CHAIN PROJECT
Using the LEAP/EDB modelling system for fuel chain analysis in developing countries

C. HEAPS, M. LAZARUS, D. HILL
Tellus Institute,
Stockholm Environment Institute-Boston Center (SEI-B),
Boston, Massachusetts, United States of America

G. MACKENZIE
UNEP Collaborating Centre on Energy and Environment (UCCEE),
Risø National Laboratory,
Roskilde, Denmark

Abstract

THE SEI/UNEP FUEL CHAIN PROJECT: USING THE LEAP/EDB MODELLING SYSTEM FOR FUEL CHAIN ANALYSIS IN DEVELOPING COUNTRIES.

The Stockholm Environment Institute-Boston Center (SEI-B), the United Nations Environment Programme (UNEP) Collaborating Centre on Energy and Environment (UCCEE), and counterparts in Venezuela and Sri Lanka have collaborated on a two-year project to develop and apply methods for incorporating environmental considerations in major fuel choice decisions. One of the principal activities of the project was the creation of a new software tool for the analysis of fuel chains, designed to work with the existing long range energy alternatives planning/environmental database (LEAP/EDB) energy-environment modelling system developed by SEI-B. Two case studies examined fuel and technology choices in a range of sectors in Venezuela (transport and electricity) and Sri Lanka (households and electricity). The comparison of full fuel chains can highlight trade-offs between local and global environmental impacts. For example, in Venezuela, diesel and compressed natural gas (CNG) were compared as fuels for buses in Caracas. It was found that, while CNG is clearly favoured in terms of local air pollutants, the full CNG fuel chain may result in higher greenhouse gas emissions than those from diesel. Overall, the project showed that a software tool such as the LEAP fuel chain program can make fuel chain analysis more accessible in a wide range of applications, by providing user friendly guidance to this complex analytical methodology and by helping to overcome local data constraints with international sources of data.

1. INTRODUCTION

The SEI/UNEP (Stockholm Environment Institute/United Nations Environment Programme) fuel chain project represents one of the first attempts at fuel chain analysis in developing countries. Conventional environmental analyses typically focus exclusively on the impacts that occur at the site where a fuel is combusted. But environmental impacts are not restricted to the site where fuels are consumed. For example, a decision to build a coal fired power plant means that more coal needs to be mined, cleaned and transported. These upstream stages, as well as downstream stages such as ash disposal and plant decommissioning, can have important environmental impacts, which will be overlooked unless the full fuel chain is considered. Therefore, in principle at least, fuel chain analysis represents the best method for making fair comparisons among energy options.

The overall objective of ongoing SEI/UNEP collaboration is to contribute to the incorporation of environmental aspects in energy planning and policy through the development of analytical methods and the implementation and dissemination of useful software tools.[1] In applying fuel chain analysis in developing countries, a number of methodological and practical questions arise: Are data sufficient or reliable? Do the results differ from those obtained by simpler methods? Can decision makers utilize these results? Is the required level of analysis appropriate for energy planners or is it more appropriate for academic researchers? Can one overcome the methodological hurdles? In this paper we attempt to deal with some of these questions, while describing the approach and findings of the SEI/UNEP project.

The principal activities of the project included the creation of a new software tool for fuel chain analysis, case studies to test whether the tool is adapted to local circumstances and data availability, workshops to disseminate the tools and develop local expertise, and the collection of representative data describing the environmental impacts of fuel chains and their inclusion in the model. These are all described in the project report [1].

1.1. Key methodological considerations

Fuel chain analysis is an analytical technique in which energy requirements are tracked through chains of conversion processes on the basis of the efficiencies and process energy requirements of each process. Coefficients (e.g. emissions per unit of fuel combusted) yield an estimate of the impacts associated with each process. Since each process can potentially require many different inputs, an analysis can quickly become quite complex. In addition, a number of other key methodological considerations must be considered.

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[1] With support from UNEP and SIDA since the mid-1980s, SEI-B has developed and enhanced the LEAP (long range energy alternatives planning) and EDB (environmental database) software tools. LEAP and EDB have now been used by more than 100 organizations in over 30 countries worldwide.

1.1.1. Non-operational phase impacts

Pre-operational phase impacts occur during the manufacture of materials and equipment used in the fuel chain. They can be significant in solar and wind fuel chains where the technologies are material intensive [2], in transport fuel chains because of the manufacture and assembly of vehicles, or in biomass fuel chains where agricultural chemicals and machinery are used for crop production. For example, the manufacture of vehicles can account for 15–20% of the total greenhouse gas emissions from a typical gasoline fuel chain for passenger transport [3]. Post-operational phase impacts are most commonly associated with the decommissioning of nuclear power plants and other facilities, the reclamation of mining lands and the disposal of solid wastes.

1.1.2. Allocation of impacts between co-products

Where co- or by-products are produced (such as electricity and cogenerated steam) a decision rule is needed to allocate 'responsibility' for environmental loadings among these products. Loadings can be allocated solely to the main energy products on the basis that a facility is built and operated primarily to produce these products, or they can be allocated among two or more energy products according to their energy content. Other alternatives are also possible, such as allocation by economic value of the product.

1.1.3. Boundary issues

Boundary issues are important in defining which effects and stages should be included in a particular analysis. When dealing with imported fuels, the question arises whether to include fuel chain stages that occur outside the country or region of immediate concern. Policy makers and the public may not wish to give significant weight to these effects.

1.1.4. Resource availability

Fuel chain analysis is normally used to evaluate the impacts of a new fuel or technology option, but any analysis must also consider the source of the additional energy requirements of the fuel chain. So, for example, an analysis must consider whether electricity used in a fuel chain can be supplied from the available capacity of an existing mix of technologies or whether new generating capacity will be needed. These issues can be difficult to analyse, especially where the resource is imported or the analysis is for some period in the future.

1.1.5. Difficult to quantify impacts

Most energy-environment studies do not attempt to quantify transport, exposure and dose response effects, or the final impact on human health and ecosystems of energy related environmental pollution. Generalized models for these effects are usually unavailable and the degree or even existence of many effects is controversial. The analysis of these issues was beyond the limited scope of this study.

2. THE LEAP/EDB FUEL CHAIN TOOL

The LEAP system and the EDB are user friendly software tools for energy-environment planning and analysis. LEAP applications include the preparation of energy-environment scenarios (e.g. for China, Costa Rica, Senegal); the analysis of greenhouse gas abatement options (for Mongolia, South Korea, Venezuela and countries involved in the US Country Studies programme on climate change); "America's Energy Choices" — a national energy study of the United States of America by the Tellus Institute; decentralized rural energy planning (Philippines); options for minimizing air transport pollution in Delhi; and two global energy and climate studies by the Tellus Institute and the International Institute for Applied Systems Analysis (IIASA).[2]

One of the principal activities of the SEI/UNEP fuel chain project was the creation of a new software tool for the analysis of the environmental impacts of fuel chains. The new tool is an integral part of LEAP/EDB and is designed to complement the software's existing integrated scenario analysis tools. The tool compares alternative fuel and technology choices on the basis of their full life cycle environmental impacts, including the loadings associated with the construction phase of fuel chain stages (e.g. the construction of vehicles and power plants). The software will be disseminated to governmental and non-governmental agencies conducting energy and environmental analysis and will include default data representative of technologies in both industrialized and developing countries. Table I lists key characteristics of the tool, and Fig. 1 illustrates the modular approach to fuel chain analysis taken by the software. The LEAP/EDB User Guide contains a complete description of the system [4].

3. CASE STUDIES

Case study countries were in part selected to give broad coverage of four important fuel chains: oil and gas (Venezuela), and coal and biomass (Sri Lanka).

[2] A list of LEAP/EDB related studies and publications is available from SEI–B.

TABLE I. KEY CHARACTERISTICS OF THE LEAP FUEL CHAIN PROGRAM

- Suitable for electricity, transport and other fuel chain analyses.
- Full life cycle tracking of energy, environmental loadings and materials use.
- Suitable for analysis of simple linear and more complex 'branching' fuel chains.
- Choice of methodologies for allocating impacts between co-products.
- Modular structure allows reusable fuel chains to be 'plugged' together.
- Recursive calculation methodology fully tracks second-order fuel chains.
- Potentially tracks all fuel chain stages from final fuel use to the point of resource extraction, but allows users to choose the boundaries of the analysis.
- Works with the EDB, which contains over 5000 documented energy related environmental impact coefficients.
- Can be used in conjunction with LEAP's integrated energy scenario tools — allowing data to be shared between analyses.
- User-friendly design, including automatic units conversion and flexible reports and graphs with automatic formatting and scaling.

In each case, the new LEAP fuel chain program was employed to study the impacts of fuel and technology choices, including the greenhouse gas emissions of each fuel chain.

3.1. Venezuela: Fuel and technology options in the transport and electricity sectors

In Venezuela, SEI–B collaborated with the Venezuelan Ministry of Mines and Energy in examining the fuel chain environmental impacts of alternative public transport and electricity generation fuel chains. The transportation analysis compared diesel and compressed natural gas (CNG) as fuels for buses in Caracas. CNG is being considered as a transportation fuel because it may have environmental advantages over diesel fuel and because using CNG can increase the amounts of diesel and gasoline available for export. In the electricity sector, residual fuel oil and natural gas were compared as sources of boiler fuel for Planta Centro, Venezuela's largest thermal electric power plant. At Planta Centro, which is in the process of being privatized, the conversion of boilers to burn natural gas rather than residual fuel oil is under active consideration.

Venezuela is a good setting for case studies of the petroleum and natural gas fuel chains. As a major producer of crude oil since the 1920s, Venezuela has developed energy planning and management infrastructures, and a wealth of data on the

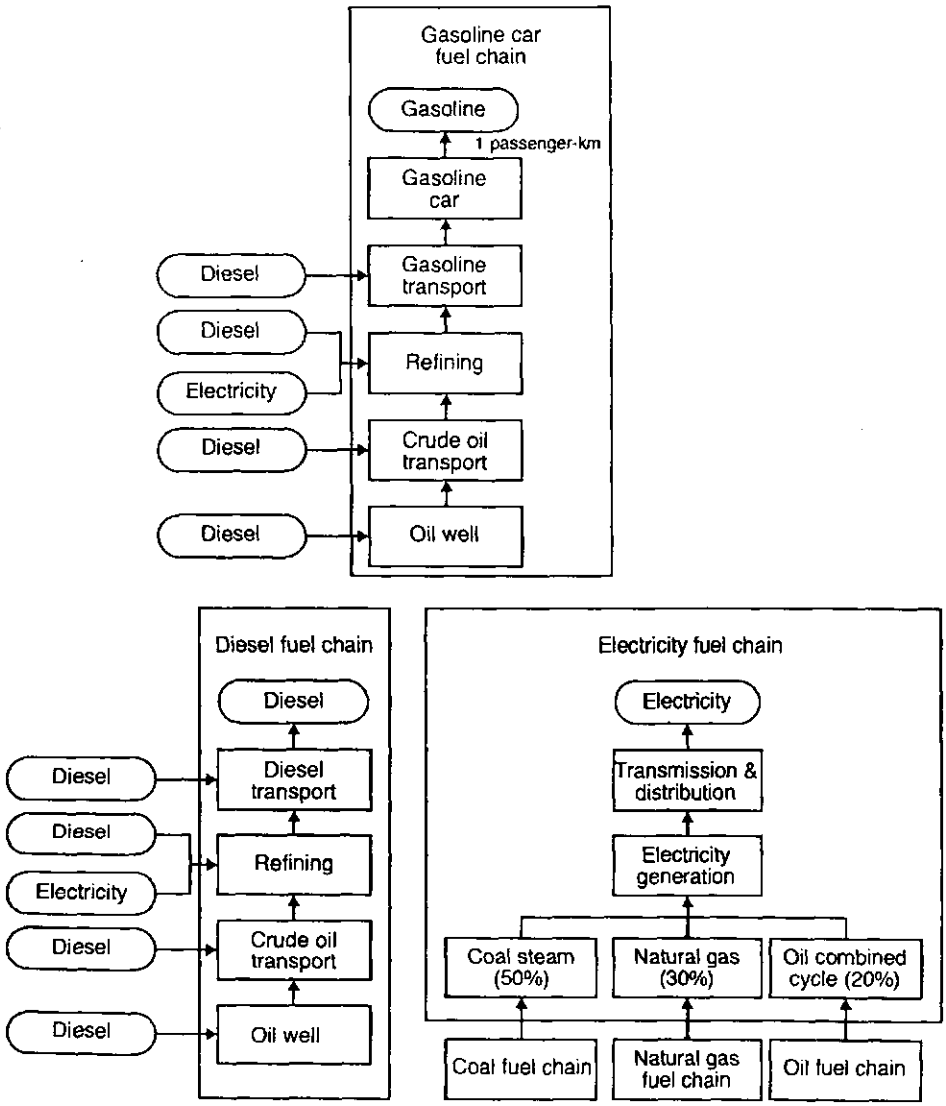

FIG. 1. Modular approach to fuel chain analysis.
Fuel chains are constructed in a modular fashion in LEAP. The principal fuel chain is named 'gasoline car' and is used to trace gasoline from the point of its final use in the car (to provide 1 passenger-km of transport service) back to the extraction of crude oil. Diesel and electricity are also used at various stages in the fuel chain. Additional fuel chains are constructed for these, which may in turn be linked to further fuel chains. For complex cases, circular fuel chain references can be created and resolved. A recursive calculation methodology is used to estimate the total energy requirements of each process. Further calculation steps are then used to calculate materials requirements, the energy required to produce those materials, and the environmental loadings of the fuel chain.

TABLE II. VENEZUELA TRANSPORT FUEL CHAINS: NET ENERGY USE, STAGE BY FUEL CHAIN
Gigajoules per million passenger-kilometres

Stage	Diesel bus	CNG bus[a]	
		Low loss	High loss
Final fuel use	577.2	663.8	663.8
Losses and auxiliary fuel use			
Electricity distribution	3.1	5.7	5.7
Natural gas compression	0.0	20.9	20.9
Electricity generation	31.4	57.5	57.5
Petroleum product distillation	0.6	0.0	0.0
Natural gas pipeline	0.7	37.8	44.8
Refining	57.4	0.4	0.4
Gas treatment	1.2	63.4	64.0
Natural gas recovery	0.8	27.1	69.2
Oil pipeline	6.2	0.0	0.0
Crude recovery	22.4	0.1	0.1
Total	701.0	876.7	926.4

[a] For CNG, two sensitivities are shown for low and high natural gas venting and flaring losses.

national energy economy is available. In addition, even though Venezuela is a major oil producer, alternatives to the domestic consumption of traditional petroleum products have been developed and continue to be actively considered or promoted. Using less exportable forms of energy, such as natural gas or hydropower, for domestic consumption increases the amount of petroleum products available for export. Environmental objectives, such as limiting urban air pollution or the emission of greenhouse gases, can also motivate analyses of alternatives to petroleum fuels.

Facilities were selected on the basis of data availability, geographic location, and their physical or economic ties to other study sites. Local data were compared with and, where necessary, supplemented with more generic international data. Data

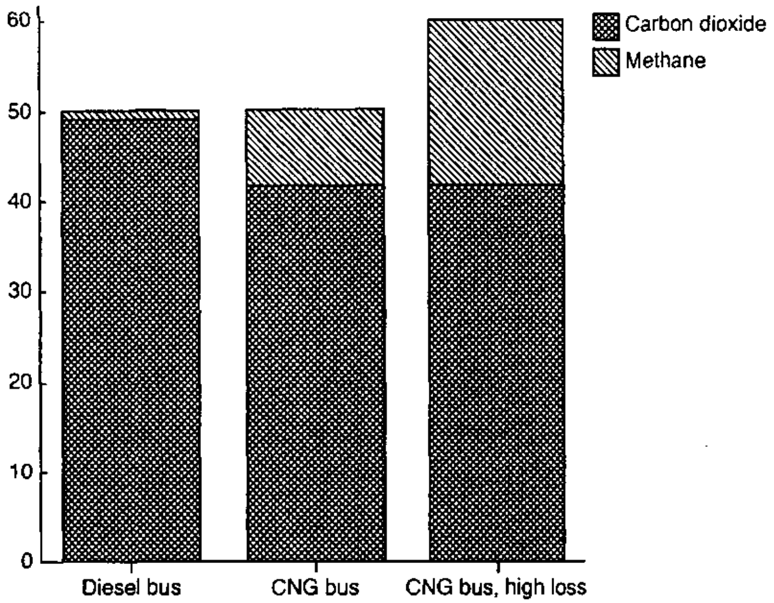

FIG. 2. Venezuela transport fuel chains: greenhouse gas emissions (t CO_2 equivalent per million passenger-km; IPCC 100 year integration, see Ref. [5]).

were collected during two visits by SEI-B staff and through follow-up surveys conducted by an independent local consultant.

The analysis was limited to the primary greenhouse gas and local air pollutant emissions of the fuel chains. Oil and gas fuel chains often produce other important environmental loadings and other diverse impacts, many of which are difficult to quantify and value, particularly in developing countries where data are less readily available. The analysis of these impacts is beyond the scope of this study.

The case study also focused on the operational phase of each fuel chain. Because the construction and decommissioning requirements for facilities used to extract, process and transport natural gas and petroleum products are relatively similar, it is unlikely that there are significant differences in the pre- and post-operational phase impacts of the fuel chains compared.

3.1.1. Transport fuel chains

CNG was compared with diesel as a potential fuel for urban buses in Caracas. Table II presents the energy use by stage of the two fuel chains. For the CNG fuel chain, the major sources of losses and auxiliary fuel use were natural gas compression at the CNG filling station, and gas venting and flaring. For the diesel chain, energy used in refining and crude recovery were important. Both fuel chains consumed significant amounts of electricity.

The diesel bus fuel chain was found to have a higher overall efficiency than the CNG fuel chain, primarily because diesel buses have a 15% fuel efficiency advantage over a comparable bus fuelled by CNG (because of engine characteristics and the additional weight required for CNG storage tanks).

Figure 2 shows the greenhouse gas emissions from the transport fuel chains. Because of methane emissions from the recovery and transmission of natural gas and the lower efficiency of CNG vehicles, natural gas is not clearly favoured over diesel as a transportation fuel as a means of limiting greenhouse gas emissions. Assuming low natural gas loss rates in production and distribution, the global warming impacts of the CNG fuel chain are approximately equal to those of the diesel fuel chain. At high natural gas loss rates, the global warming potential for the CNG fuel chain is 27% greater than that for the diesel fuel chain.

These findings raise interesting issues about how to correctly allocate the impacts of fuel chains. Our results are based on the assumption that natural gas would come from additional production rather than from recovery from existing sources that would otherwise be flared, vented or leaked. Because of the higher economic costs of capturing natural gas from losses, this appears to be the most relevant assumption. If, however, captured losses were assumed to be the marginal source of natural gas in a CNG vehicle programme, then the CNG fuel chain could be assigned a sizable credit with respect to greenhouse gas emissions because of the reduction in methane emissions.[3]

3.1.2. Electricity generation fuel chains

As Fig. 3 shows, in terms of greenhouse gas emissions, natural gas is the preferred fuel for electricity generation, even under the assumption of relatively high natural gas system losses. The global warming potential of natural gas fired electricity is 12–27% lower than that of residual fuel oil per kilowatt-hour (depending on methane loss assumptions).

Overall, therefore, natural gas is more effective in terms of greenhouse gas abatement if it is used as a substitute for residual fuel oil in electricity generation rather than as a replacement for diesel in transportation. With respect to emissions of local air pollutants, CNG is clearly favoured over diesel as a bus fuel, and natural gas is clearly favoured over residual fuel oil for electricity generation.

[3] To obtain the credit, one would have to be able to say that natural gas losses would not be reduced unless a CNG vehicle programme were pursued. If a credit were given, it would make the CNG option enormously beneficial in terms of global warming potential, since each avoided tonne of methane is equivalent to about 25 t CO_2, based on a 100 year integration period.

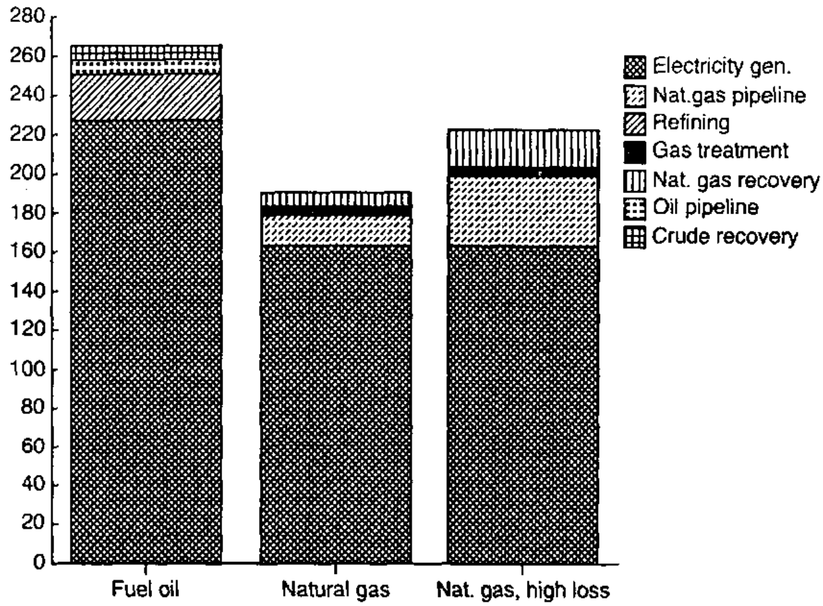

FIG. 3. Venezuela electricity fuel chains: greenhouse gas emissions by stage (kg CO_2 equivalent per gigajoule final energy; IPCC 100 year integration, see Ref. [5]).

3.2. Sri Lanka: Fuel and technology options in the household and electricity sectors

In Sri Lanka, SEI-B worked with the Ceylon Electricity Board (CEB) to develop fuel chain analyses for a range of alternative household fuel and electricity generation options. In the household sector, biomass fuels were compared with liquefied petroleum gas (LPG), while, in the electricity sector, biomass was compared with coal.

Like many other developing countries, Sri Lanka is currently experiencing a transition from the predominant use of biomass fuels to the use of 'modern' fuels. While biomass remains the dominant fuel, the consumption of modern fuels, such as electricity and kerosene for lighting and LPG for cooking, is growing rapidly. Sri Lanka now faces difficult choices regarding how to meet the energy needs of its growing population. It has no indigenous fossil fuel resources and, until now, has relied exclusively on hydropower and imported oil to meet the demands for modern fuels. The remaining potential for large scale hydroelectric power development is rapidly being exhausted and so, in the future, Sri Lanka will have to turn to other energy resources.

The present juncture in Sri Lanka's development therefore provides an opportunity to compare and contrast the different energy options available. The question is whether Sri Lanka should pursue an energy system that will require reliance on imported fossil fuel resources such as coal and oil, or whether it should seek to develop its indigenous renewable resources, foremost among which is biomass. In this case study we have explored one dimension of this question: the environmental implications of those fuel choices.

Fuel chain analysis in Sri Lanka presents an interesting contrast to the challenges faced in Venezuela. In Sri Lanka, local data are sparse, particularly concerning biomass consumption and production. So, for example, the sustainability of fuelwood supplies can only be roughly estimated. Moreover, the energy policy options to be considered are less well defined than in Venezuela. In the electricity sector, for example, the long term planning process is in a state of flux, pending Government deregulation. Studies of even the most likely near term electricity generation alternatives are currently little more than initial feasibility studies and environmental impact assessments. This places emphasis on the use of international sources of energy and environmental data, and on the need for informed assumptions, for example regarding the source and type of coal that might be used in Sri Lanka.

3.2.1. Household fuel chains

Almost 93% of the island's population use biomass fuels for cooking. The main sources of firewood are the uprooting of wood at rubber plantations, supplies from natural forests, coconut wood, forest plantations and other sources [6]. Biomass fuels are often regarded as a means to reduce greenhouse gas emissions by replacing fossil fuels. However, our fuel chain analysis for Sri Lanka shows that this assumption is dependent on highly uncertain data about the sustainability of fuelwood production. Unless firewood is produced in a sustainable fashion, LPG, with its characteristic high end use efficiency, may actually produce lower net emissions of greenhouse gases per unit of useful energy consumed. Although we were unable to determine the current level of sustainability of firewood production in Sri Lanka, or to predict the future level, we were able to calculate a break-even point of 78% sustainability for fuelwood supplies, below which LPG produces lower overall greenhouse gas loadings (see Fig. 4). It should be noted that this is higher than the 69% of household fuelwood supplies that come from sustainable sources of supply.[4] At the same time, local policy concerns about the potentially harmful

[4] According to the 1986 Forestry Master Plan (which was being revised at the time of this study — see Ref. [7]), sustainable sources of fuelwood (coconut, rubberwood, tea and rubber prunings, home gardens and forest plantations) account for 69% of household fuelwood supplies. The sustainability of supply of the remaining 31%, most of which comes from natural forest areas, is unknown.

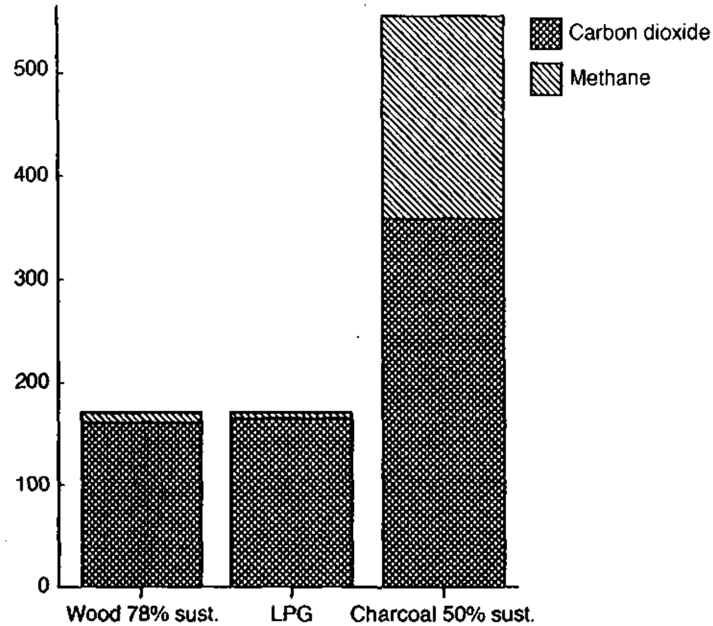

FIG. 4. Sri Lanka household fuel chains: global warming potential (t CO_2 equivalent per 1000 GJ useful energy; IPCC 100 year integration, see Ref. [5]).

effects of indoor air pollutants point towards the promotion of cleaner burning fuels such as LPG.

Charcoal has in the past been produced solely from cleared woodlands. It has a significantly higher global warming potential than both firewood and LPG, regardless of assumptions about the sustainability of fuelwood supplies (see Fig. 4). This is due to the large amounts of methane emitted during charcoal production. In terms of its global warming potential, charcoal therefore appears an unattractive option.

3.2.2. Electricity fuel chains

The potential for biomass electricity generation in Sri Lanka is large but remains mostly untried.[5] In 1991, industries in Sri Lanka consumed approximately 1.05 million tonnes of firewood [7], of which the tea industry consumed about 40%. If the all the wood currently used by the tea industry to wither and dry leaves were utilized instead for cogeneration of steam and electricity, using a conventional steam

[5] According to the CEB, small amounts of non-grid electricity are already being produced by the sugar industry.

TABLE III. SRI LANKA ELECTRICITY FUEL CHAINS: EFFECT BY FUEL CHAIN
Per 1000 GJ final energy

	Coal steam	Eff. coal	Biomass steam	Eff. biomass (kg)
Carbon dioxide				
Non-biogenic	297.1	270.3	5.1	2.6
Biogenic	0.0	0.0	1115.4	608.4
Carbon monoxide	274.9	28.7	83.7	5.7
Methane	772.3	698.2	86.5	5.9
Nitrogen oxides	1155.6	663.7	494.9	147.5
Sulphur oxides	2129.1	698.5	8.9	4.5
Particulates	4356.6	46.3	13.7	6.9

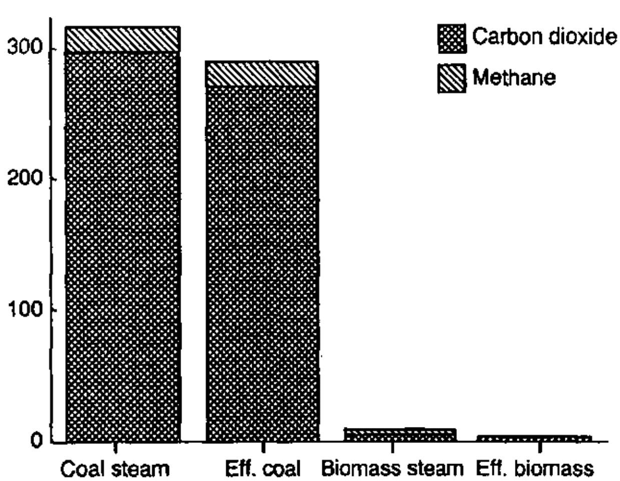

FIG. 5. Sri Lanka electricity fuel chains: global warming potential (t CO_2 equivalent per 1000 GJ; IPCC 100 year integration, see Ref. [5]).

fired plant, then approximately 340 GW·h of electricity, or about 10% of the total electricity generated in Sri Lanka, could be produced whilst still meeting the process heat requirements of the industry.

Our baseline analysis used available data from the proposed Trincomalee coal fired power plant [8], combined with emissions factors taken from standard US data sources [9]. Coal was assumed to be transported from either Australia or South Africa. The energy use and emission loadings from the upstream coal transport and mining stages were included in the analysis. The coal mining impacts of surface and underground mines vary significantly (for example, in terms of methane emissions and health and safety impacts). The total fuel chain impacts were therefore calculated using two representative technologies, 'surface' and 'underground', which were weighted by the amount of each type of coal currently produced in Australia [10]. The coal plant technology was compared with biomass power plant technologies based on conventional steam turbines, with data culled from various data sources (e.g. Ref. [11]). Because of uncertainties regarding the time-scale and structure of electricity capacity expansion in Sri Lanka, we also conducted sensitivity analyses to examine the effects of using cleaner coal and more efficient biomass systems.

The results of our analysis illustrate the overwhelming environmental benefits of biomass fuel chains compared with coal fuel chains, especially in terms of greenhouse gas emissions. Even allowing for upstream emissions from diesel fuels (for fuelwood transport) and fertilizer manufacture and application, it is found that biomass still produces much lower emissions of most pollutants than coal, as shown in Table III. The benefits of sustainably produced biomass over coal are particularly evident in terms of the total greenhouse gas loadings of each fuel chain (see Fig. 5).

The financial viability of biomass systems depends on easy access to low cost or zero cost sources of fuels. For this reason, the most promising first application of biomass is in existing industries, where biomass fuels are already being utilized to produce process heat. In the longer term, questions remain about how quickly high efficiency biomass systems can be developed, and whether sufficient irrigation and suitable high yielding tree species can be found for Sri Lanka's dry zones. Overall, though, modern biomass applications appear particularly promising in view of the absence of fossil fuel resources in the country.

Given the policy alternatives in Sri Lanka today, we found, perhaps not surprisingly, that biomass has more environmental benefits as a fuel for electricity generation than as a fuel for households. This finding is partly due to the fact that biomass was compared with coal in the electricity sector and with LPG in the household sector. Coal is probably the most polluting of the fossil fuels, while LPG is one of the cleanest fuels. At the same time, it should be emphasized that our analysis only examined the environmental impacts of these fuel and technology options. We did not undertake a detailed financial analysis of their viability, nor did we examine the economics and environmental impacts of alternative land-use options. Further analysis is required before firm policy conclusions can be drawn.

4. CONCLUSIONS

The SEI/UNEP fuel chain project demonstrates that fuel chain analysis can be a useful tool for evaluating the environmental consequences of fuel choice decisions in developing countries. Fuel chain analysis forces the analyst to explicitly draw boundaries around systems and to allocate impacts within and between co- and by-products of the energy system[6] — tasks which are not necessarily simple or obvious, but which are nonetheless important in forming rational energy policies. However, fuel chain analysis is also a data and labour intensive activity, so that detailed studies (even those limited to a small number of impacts) may lie beyond the analytical objectives, institutional capabilities and time constraints of some national energy planning agencies.

A software tool such as the LEAP fuel chain program can make fuel chain analysis more accessible in a wide range of applications by providing user friendly guidance to this new and complex analytical methodology, and by helping to overcome local data constraints with default energy and environmental data. Technology and environmental databases are particularly useful in connection with developing countries where planners are attempting to compare the environmental consequences of developing new resources and/or technologies. In such cases, local data often will not be available, and well documented sources of international data provide the best chance of promoting rational decision making.

The results of the Venezuela and Sri Lanka case studies show that the comparison of fuel chains often presents distinct trade-offs between different local and global environmental impacts (e.g. local air pollution versus global warming). Damage estimation and valuation exercises provide one means to integrate these costs and benefits with standard financial and economic criteria to come up with an ostensibly more 'objective' finding. However, this approach may prove overly heroic, given the uncertainties in the data and in our understanding of environmental pathways, and because of the many subjective factors that affect decision making. Investigation of integration and valuation techniques and their inclusion in these types of software tool is one promising area for further research.[7]

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[6] In Sri Lanka, for example, when assessing the impacts of imported coal, an analyst must decide whether to include the impacts of the coal mining and transport stages; or, when considering fuelwood sustainability, an analyst must assess the extent to which deforestation is due to fuelwood consumption pressures.

[7] See, for example, Ref. [12], which is a study of how multicriteria analysis might be used to incorporate externalities into decision making in the power sector.

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ASSESSMENT OF ENVIRONMENTAL ISSUES USING SUPER-OLADE/BID FOR COMPARING ALTERNATIVE ELECTRICITY SYSTEM EXPANSION STRATEGIES
A case study for Colombia

R. CAMPO
Consultant,
Bogota

E. ANGEL
Interconexión Eléctrica S.A.,
Medellin

D. GOMEZ, O.L. LEON
Empresa de Energía de Bogotá,
Bogota

Colombia

Abstract

ASSESSMENT OF ENVIRONMENTAL ISSUES USING SUPER-OLADE/BID FOR COMPARING ALTERNATIVE ELECTRICITY SYSTEM EXPANSION STRATEGIES: A CASE STUDY FOR COLOMBIA.

SUPER is a modular package for electricity generation expansion studies. It includes an environmental impacts module (EIM), originally developed by Interconexión Eléctrica S.A., the operator of the Colombian Power Pool, and adapted for use by utilities with a large hydro component. The paper describes the EIM and illustrates its application to a recent study.

1. INTRODUCTION

The environmental impacts module (EIM) of the modular package for electricity generation expansion studies SUPER is based on an additive multi-objective function which for a given project (or a set of projects) attempts to:

- minimize the impact on the physical environment,
- minimize the impact on the local biota,
- minimize the displaced population,
- minimize regional costs,
- maximize regional benefits.

For ease of reporting, SUPER aggregates these objectives in three macro-objectives: the first two in the physico-biological objective and the next two in the regional costs objective. The fifth objective remains unchanged.

Value judgements of decision makers are used to assign weights to the various objectives. In the case of Colombia, the weights adopted were arrived at by a consensus of the representatives of all electrical utilities. In SUPER, the weights can be changed so that they better reflect the particular circumstances of the utility under study.

This module is not intended to replace environmental impact studies but rather to use their results in an integrated way that allows projects and expansion strategies to be compared.

2. OBJECTIVES, CRITERIA AND VARIABLES

Objectives are disaggregated into criteria which express the impacts. Criteria are made up of variables that are quantified by indicators especially designed for each variable. The value of an objective depends on the value of its criteria through a function that corresponds to a mixture of exponentials. A list of the criteria associated with each of the objectives is given below.

Objective: Minimization of the impact on the physical environment

Criteria:

(a) Stability of the project zone,
(b) Increase in the inflow into the receptor basin,
(c) Reduction of inflow,
(d) Water quality,
(e) Air quality.

Objective: Minimization of the impact on the local biota

Criteria:

(a) Impact on the biota of land ecosystems,
(b) Impact on the biota of water ecosystems,
(c) Impact on the biota of other ecosystems.

Objective: Minimization of the displaced population

Criterion:

(a) Displaced population.

Objective: Minimization of regional costs

Criteria:

(a) Area required for the project,
(b) Lost production,
(c) Loss of historical patrimony,
(d) Degradation of social order,
(e) Social trauma,
(f) Displaced employment,
(g) Increase in the likelihood of local conflicts.

Objective: Maximization of regional benefits

Criteria:

(a) Improvements of roads,
(b) Benefits other than energy related ones,
(c) Improvements in rural electrification,
(d) Improvements in social investments,
(e) Creation of employment,
(f) Regional improvements enforced by law.

As an example, we give a detailed explanation of the criterion displaced population. It refers to the people who had to leave their homes, or their place of work,

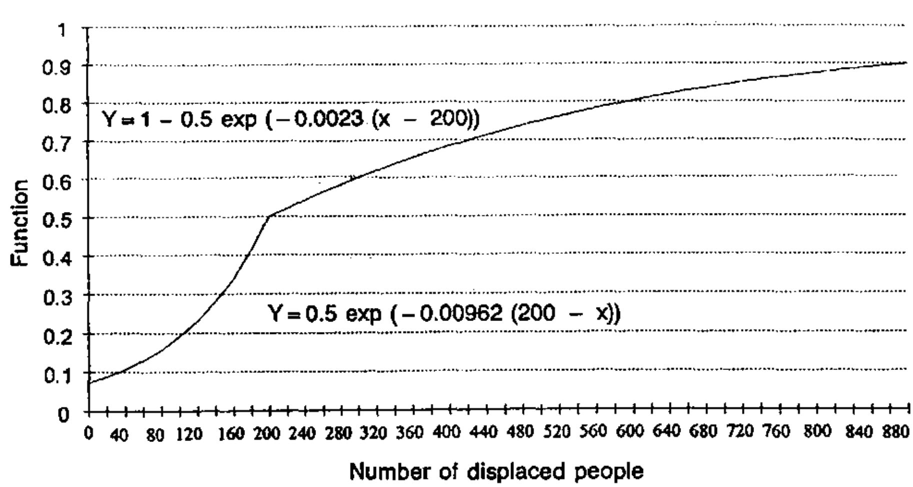

FIG. 1. Impact on the displaced population.

or both, because of the impact of an energy project. The impact of displacement depends on how vulnerable the affected people are. Vulnerability can be defined as capacity to adapt. In this sense, the impact of displacement is larger when it affects ethnic minorities or a population that is strongly dependent on the surrounding natural environment; the impact is less severe when, for example, the dependence of land owners on this environment is low.

For this criterion the following indicator is introduced:

$$\sum f \cdot v$$

where f is the number of affected families, differentiated by their degree of vulnerability into ethnic minorities and into small, medium and large agricultural producers; v is the differential vulnerability of each group of families. The following values are given for the degree of vulnerability:

— Ethnic minorities	1.0
— Small producers	0.7
— Medium producers	0.3
— Large producers	0.05

Small producers are, for example, small land owners, colonists and their families, small-scale miners and subsistence anglers. Medium producers sell their products on the market, accumulate small capitals and depend on the market economy and the payment of labourers.

Once the indicator for the criterion displaced population has been evaluated, its impact can be quantified by using the double exponential function given in Fig. 1.

The remaining criteria are assessed in a similar way. The SUPER Reference and User Manuals contain a detailed description of all criteria, indicator variables and evaluation functions used to obtain values for the objectives and for the overall objective function. Furthermore, these manuals include relevant references to the special literature.

3. CASE STUDY

Two scenarios have been defined for the environmental study of Empresa de Energía de Bogotá (EEB)[1]: the reference scenario and the pessimistic scenario. The last one assumes increases in the values of demographic variables. For each scenario

[1] Generation Expansion Plan of EEB, 1994.

TABLE I. ENVIRONMENTAL EVALUATION OF PROJECTS (REFERENCE SCENARIO)

Project	Macro-objectives			Total
	Physico-biological	Regional costs	Regional benefits	
Guayabetal	0.106	0.143	0.439	0.025
Tasajero II	0.180	0.119	0.450	0.046
Miel I	0.106	0.128	0.555	0.050
Ovejas	0.074	0.118	0.149	0.052
C. Centro I	0.137	0.126	0.287	0.059
C. Valle	0.109	0.126	0.200	0.061
La Loma	0.270	0.128	0.507	0.078
Paipa IV	0.279	0.124	0.425	0.095
Fonce	0.162	0.279	0.466	0.098
Quetame	0.243	0.196	0.466	0.100
Porce II	0.177	0.267	0.455	0.102
Zipa VI	0.268	0.161	0.428	0.106
San Jorge I	0.330	0.184	0.608	0.108
Tibita	0.377	0.176	0.658	0.117
Riachon	0.272	0.182	0.297	0.137
Humea	0.337	0.248	0.458	0.163
Nechi	0.429	0.266	0.521	0.198
Sogamoso	0.357	0.391	0.449	0.229
Urra	0.405	0.737	0.631	0.354
Upía	0.361	0.813	0.607	0.370

an environmental evaluation was made, using SUPER, obtaining as a result the ordering of the projects to be included in the expansion strategy (see Table I and Fig. 2).

When the reference scenario is replaced by the pessimistic scenario, only the relative order of the hydroelectric project Quetame changes: from the 10th position (total impact equal to 0.10) to the 13th position (total impact equal to 0.12). It can be concluded that the ordering obtained is robust with respect to uncertainties in the impact of demographic variables, which was found to be the largest one.

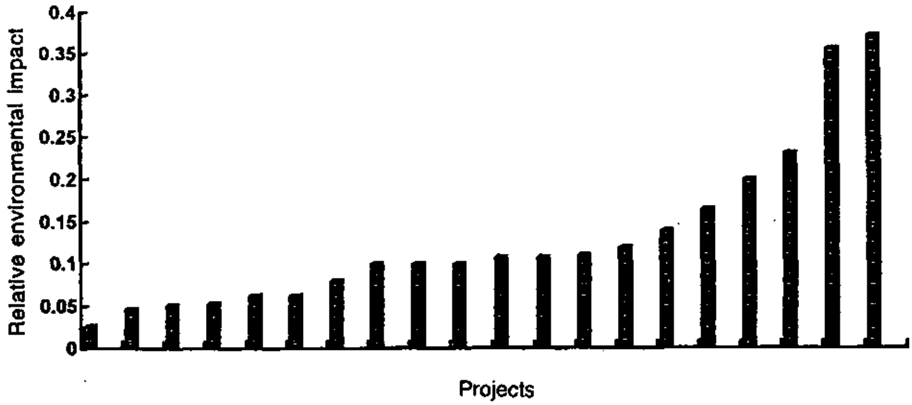

FIG. 2. Environmental ordering of projects (reference scenario, see Table I).

From Fig. 2 it can be seen that the relative environmental impacts of candidate projects range from 0.025 (for Guayabetal) to 0.370 (for Upía). From an environmental point of view, three groups of projects can be established. The impacts on the first group are in the range of 0.025 to 0.078 and include hydro run-of-river and combined cycle projects. The impacts on the second group vary from 0.095 to 0.137; this group includes hydro projects with medium size reservoirs and coal based thermal plants. The impacts on the third group vary from 0.163 to 0.370, corresponding to hydro projects with large reservoirs.

The environmental ordering of the projects in Fig. 2 does not necessarily agree with the order in which projects appear in the official development plan. As a matter of fact, some of the most benign environmental projects do not appear in this plan, which suggests the need to add to the cost of projects the cost of mitigating their environmental impacts. On the basis of the analysis made with SUPER, impacts can be identified, and for each project the costs of mitigating its environmental impacts can be estimated. Table II gives the environmental costs as a percentage of the cost of each project. In general, the highest costs correspond to hydro projects with large reservoirs and are due to the cost of relocating the displaced population.

4. CONCLUSIONS

The EIM of SUPER provides an ordering of projects regarding their environmental impacts and permits the performance of sensitivity analyses to check the robustness of the ordering under changes in the values of uncertain variables. The EIM identifies for each project the particular variable(s) that is (are) responsible for

TABLE II. COST OF MITIGATING ENVIRONMENTAL IMPACTS
(million US $ of December 1993)

Project	Capacity (MW)	Environmental cost (% of project cost)
Guayabetal	370	10.10
Tasajero II	1 × 300	9.50
Miel I	375	6.76
Ovejas	2.7	0.10
C. Centro I	1 × 300	6.00
C. Valle	1 × 150	2.90
La Loma	1 × 300	9.84
Paipa IV	1 × 150	4.89
Fonce	420	10.61
Quetame	230	10.54
Porce II	393	12.25
Zipa VI	1 × 150	7.28
San Jorge I	1 × 300	14.27
Tibita	1 × 300	14.21
Riachon	90	4.75
Humea	275	16.17
Nechi	591	22.64
Sogamoso	850	34.49
Urra	340	23.41
Upía	1332	10.00

the largest share of the environmental impact of a project and thus facilitates economic studies performed to determine the best way of reducing this impact. The EIM provides for potential investors valuable insights into the environmental implications of various projects and the type of studies needed to secure environmental licences.

IMPLEMENTATION OF COMPARATIVE ASSESSMENT
Country Case Studies

(Session 5)

Chairman

C. CORDOBA SALAZAR
Colombia

EVALUATION OF POLICY MEASURES TO CONTROL CARBON DIOXIDE EMISSIONS IN SWEDEN

T. LARSSON
Energy Systems Technology,
Chalmers University of Technology

B. RYDÉN, H. SKÖLDBERG
Profu Consultants

Göteborg, Sweden

Abstract

EVALUATION OF POLICY MEASURES TO CONTROL CARBON DIOXIDE EMISSIONS IN SWEDEN.

The effects on CO_2 emissions in Sweden of three energy policies on energy taxes and subsidies are compared. The three policies are: (a) the energy policy of 1990: energy taxes in effect from 1 January 1990; (b) the energy policy of 1994: energy taxes in effect from 1 July 1994, together with a number of subsidies in effect throughout the period 1994–1996; (c) the energy policy of 1994, with extended support: this is the same as under (b), but with subsidies in effect throughout the period 1994–2002. The main differences between the tax system of 1994 and the one of 1990 are: the introduction of emission fees on SO_2 and NO_x, the introduction of value added tax on energy, reduced tax rates for the industrial sector and increased tax rates for households. The study covers the whole Swedish energy system, including the transportation sector, for the period 1990–2014. For the analysis, the Markal model, developed in the framework of the International Energy Agency, has been used. Markal is a dynamic linear programming model of the technical energy system and describes the whole energy system from extraction of resources to conversion into useful energy. The model selects the mix of energy carriers, and conversion, conservation and abatement technologies that best satisfies the system objective of minimizing the total discounted system cost within the specified emission constraints. A real discount rate of 5% was used and sensitivity runs were made for a discount rate of 10%.

1. INTRODUCTION

The Swedish national report regarding the United Nations Framework Convention on Climate Change was presented to the United Nations in September 1994. The Swedish Government requested background material from four governmental agencies, among them the National Board for Industrial and Technological Development (NUTEK); the report from NUTEK is presented in Ref. [1]. The comparison of policy measures presented here was used as background material in Ref. [1] and is presented in more detail in Ref. [2].

For the analysis, the Markal model [3–5] developed in the framework of the International Energy Agency (IEA) has been used, which describes the existing energy system as well as all possible alternative energy technologies and energy flow paths. The model selects the combination of energy technologies and energy flow paths that best satisfies the specified system objective over the period studied (usually 25–40 years). The system objective is usually expressed as minimum total system cost with a real rate of discount of $r\%$, with r typically 4–6%. The inputs are: useful energy demand by sector region, quality and duration; prices and availability of energy carriers on the market outside the system boundary; the cost and the technical properties of existing and new energy technologies; and constraints on the system's impact on the physical environment in the form of emissions, land use, etc.

Markal is a dynamic linear programming model of the technical energy system. The model was developed within a multinational framework of the IEA. This co-operation of different countries continued within the Energy Technology Systems Analysis Programme (ETSAP) [6], which is now concentrating on the greenhouse effect (Annex V). The model has been used frequently to aid decision makers in national, regional and local applications in a wide range of countries. Examples of national studies can be found in Refs [6–8], regional studies in Ref. [9] and local studies in Refs [10, 11]. Over the years, Markal has been extended to include new features. To evaluate hedging strategies, sequential decision making has been included in Markal [12, 13]. To study the trade of electricity between regions, multiple electricity grids have been introduced [9, 14]. Markal has also been merged with a macroeconomic growth model to form Markal-Macro [15].

2. DATA AND ASSUMPTIONS

A full documentation of the Markal database is given in Ref. [16]. Only the data most relevant for the evaluation of the results are presented here. The full database contains around 240 technologies.

Energy demand is divided into 18 demand categories: eight for residential and commercial, five for industry and five for transportation. The energy demand for residential and commercial is expected to be almost stable, while that for industry and transportation is expected to grow more rapidly.

For the analysis, a real rate of discount of 5% has been used, with sensitivity runs for a discount rate of 10%.

Energy taxes as of 1 January 1990 are presented in Table I. Electricity generation in condensing power plants was exempt from tax. For combined heat and power (CHP) generation there was no energy tax for the part of the fuel consumption that could be attributed to electricity generation, while the fuel used for heat production

TABLE I. ENERGY TAXES AS OF 1 JANUARY 1990 (SEK/MW·h)

Fuel	Tax
Light fuel oil	109
Heavy fuel oil	100
Hard coal	62
Liquefied petroleum gas	16
Natural gas	32
Electricity, households	92
Electricity, industries	70

TABLE II. ENERGY TAXES AS OF 1994 (SEK/MW·h)

Fuel	Energy tax, non-industry	CO_2 tax, non-industry	CO_2 tax, industry
Light fuel oil	56	96	24
Heavy fuel oil	52	89	22
Hard coal	31	110	27
Liquefied petroleum gas	8	78	20
Natural gas	17	66	17
Electricity	88	—	—

was taxed. There was no value added tax (VAT) on energy, and no tax on sulphur emissions.

The new tax system of 1994 is presented in Table II. Industries do not pay any fuel taxes and they pay only a reduced CO_2 tax. Electricity generation in condensing power plants is still exempt from all taxes. For CHP production there are no energy taxes and there is no CO_2 tax for the part of the fuel consumption that can be attributed to electricity generation. There is a full CO_2 tax and a fuel tax reduced by 50% for the fuel used for heat generation. For deliveries of district heat to industries, a subsidy of 90 SEK/MW·h is paid to the deliverer to compensate for the differences in taxes paid by industries and utilities. The VAT is 25% on all final consumption of energy. For fossil fuels there is a sulphur tax of 30 SEK per kg sulphur, and an NO_x tax has also been introduced for larger units.

The tax system of 1994 also included some temporary subsidies, which are in effect through 1996. The subsidies are presented below:

— An investment subsidy of 4000 SEK/kW(e) for biomass fuelled CHP plants;
— An investment subsidy of 35% of the investment cost for wind power plants;
— An investment subsidy of 35% of the investment cost for solar heating plants;
— A subsidy of 88 SEK/MW·h for electricity generation from wind power.

A scenario assuming continuation of these subsidies until the year 2002 has also been studied.

3. RESULTS

The scenarios studied show that the changes made in the energy policy during the period 1990–1994 have reduced the CO_2 emissions (See Fig. 1). Three sub-periods have been analysed:

(a) 1990–1994, i.e. the period during which the changes in the energy policy were made. The model results show that the new energy policy contributed to a decline in CO_2 emissions, so that the present level is 3–5% below what it would be if the 1990 policy were still in use.

(b) 1994–2005, i.e. the period from now until the start of the nuclear phase-out. For this period the model results indicate even stronger differences in emissions between the policies. The CO_2 emissions by the year 2005 are expected to be 20% below what they would be if the policy of 1990 were still in use.

The extended support for biomass fuelled CHP production will lead to an expansion of these technologies by the turn of the century, since subsidies for them will no longer be available after the start of the nuclear phase-out. Therefore, the relative decline in emissions will continue until the year 2005; afterwards the emissions will level out. The continuous decline in CO_2 emissions from 1990 to 2005 is due to the increased emissions from coal condensing power plants in the reference case (see Fig. 2).

(c) Beyond 2005, i.e. in the period after the start of the nuclear phase-out. Regardless of the policy (1990 or 1994), the CO_2 emissions will rise drastically (see Fig. 2). A policy for curbing CO_2 emissions must at least address the choice of fuel and technology for electricity generation to be effective.

For the results presented above, a real discount rate of 5% has been used. A doubling of the discount rate to 10% would reduce the differences between the policies but the direction of the trend would not change (see Fig. 3).

The changes in overall CO_2 emissions are rather small between the scenarios, but the changes within the energy system are very large. Figure 4 shows the changes in CO_2 emissions for biomass fuelled plants. The 1994 policies favour the use of

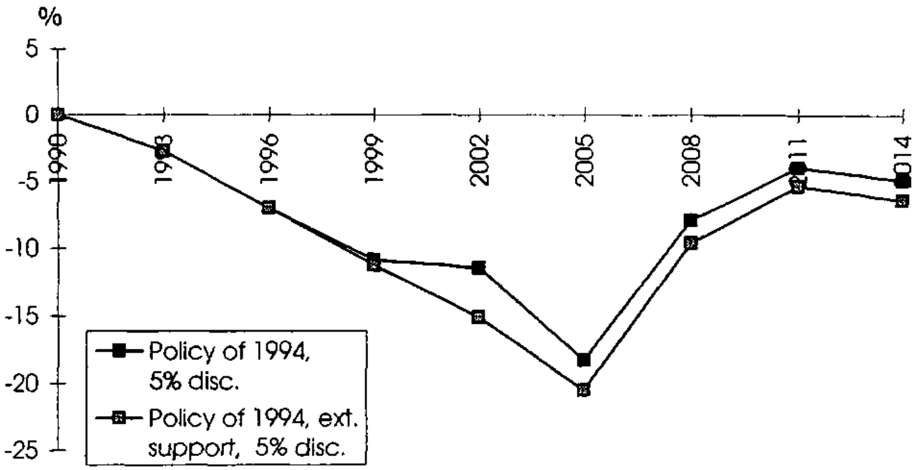

FIG. 1. Reduction of CO_2 emissions relative to the policy of 1990 for the two policies of 1994. Real discount rate: 5%.

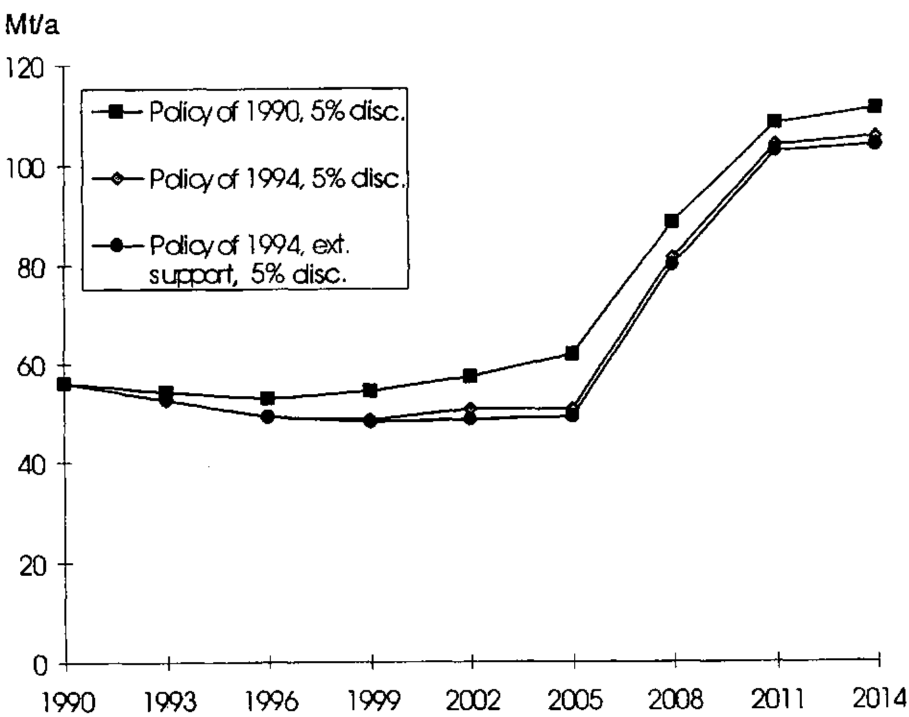

FIG. 2. Total CO_2 emissions. Real discount rate: 5%.

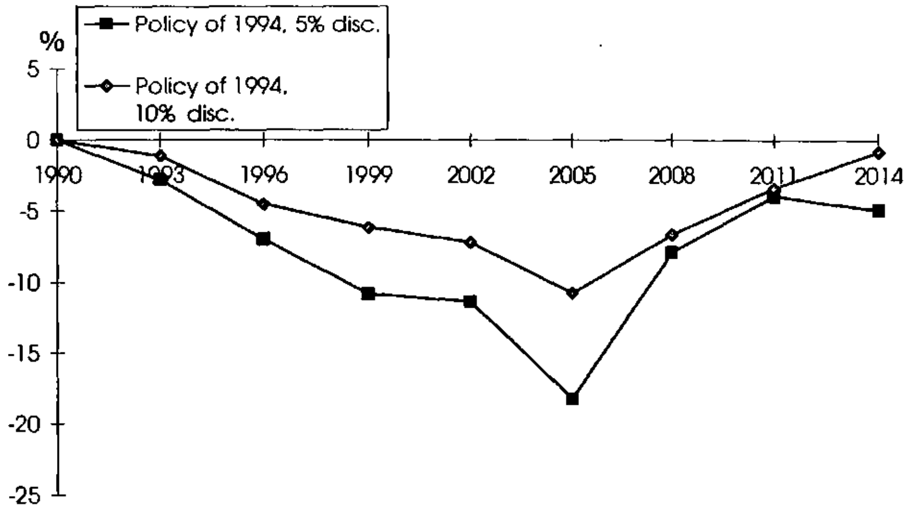

FIG. 3. Reduction of CO_2 emissions relative to the policy of 1990 for the two policies of 1994. Real discount rate: 10%.

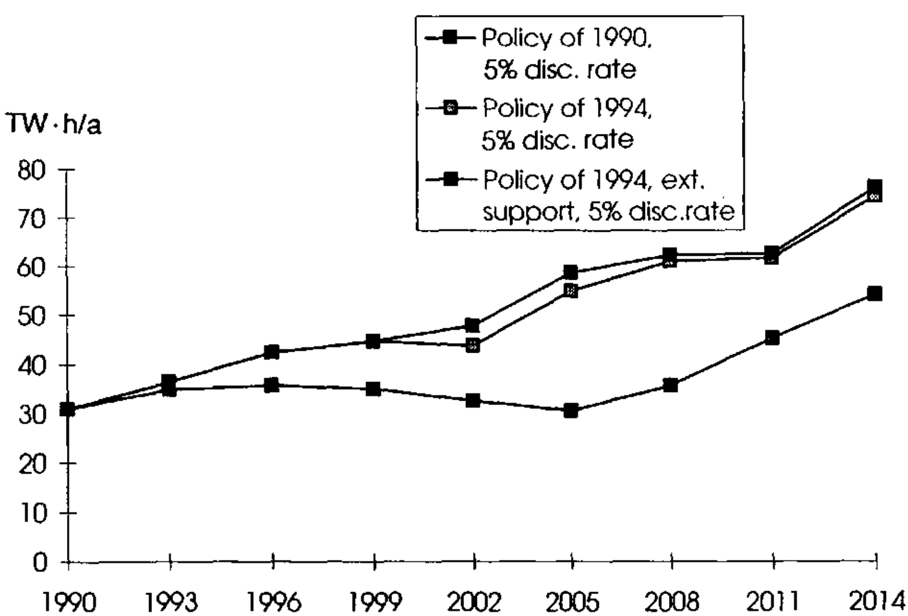

FIG. 4. Use of biomass (black liquor not included).

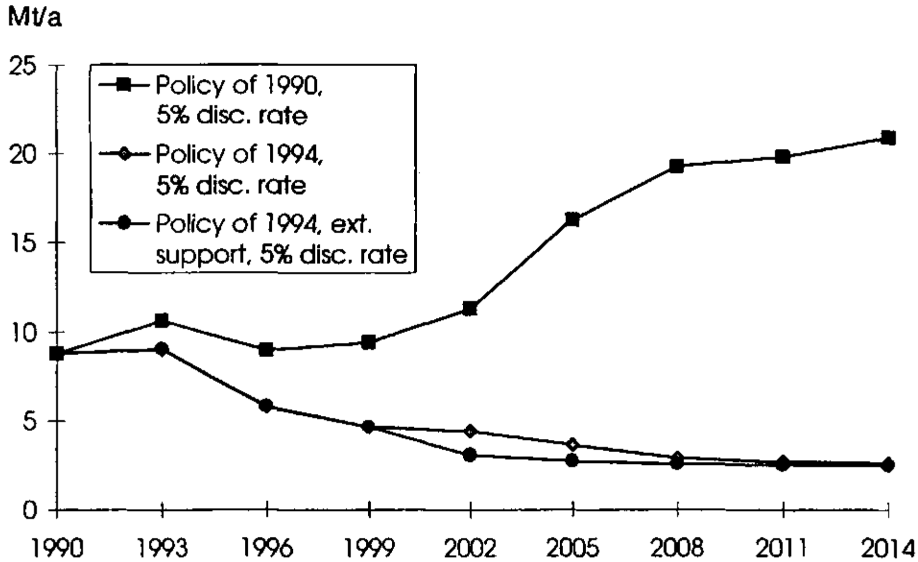

FIG. 5. Emissions of CO_2 from the district heating system.

biomass, which would grow steadily throughout the period. If the 1990 policy were still applied, the use of biomass would remain stable until the start of the nuclear phase-out and would then begin to grow rapidly. If the discount rate were changed to 10%, there would be little change compared with the 5% case for the first two phases of the period studied, while the difference between the policies would decrease beyond the year 2005.

District heating systems are very flexible. A large number of technologies are available. However, these technologies are capital intensive with long lifetimes. This means that district heating is cost effective under most policies, but adaptation of the systems to the different policies will cause problems if their direction changes too frequently. Figure 5 presents the CO_2 emissions from district heating systems for the three policies. If the policy of 1990 were still in use, the CO_2 emissions from district heating systems would double, whereas with the 1994 policies the emissions would be halved. Under the 1994 energy policy the use of biomass is favoured. Furthermore, generation from condensing power plants is exempt from tax, whereas for the part of the fuel that can be attributed to heat generation there is a tax on CO_2 emissions. The production mix for district heating for the three policies is given in Table III.

The decrease in electricity generation from CHP plants is more than compensated by electricity generation with other technologies, primarily coal condensing.

TABLE III. PRODUCTION MIX FOR DISTRICT HEATING (TW·h(th)/a)

	1995			2000			2005			2010		
	Policy 1990	Policy 1994	Policy[a] 1994	Policy 1990	Policy 1994	Policy[a] 1994	Policy 1990	Policy 1994	Policy[a] 1994	Policy 1990	Policy 1994	Policy[a] 1994
Coal CHP	2.8	1.2	1.2	3.8	0.9	0.9	13.0	0.3	0	19.9	0.1	0
Coal boiler	11.0	0.6	0.6	10.9	0.9	0.9	17.8	0	0	16.0	0	0
Bio CHP	0.9	1.4	1.4	0.8	0.9	0.9	0	0	7.3	0	4.8	7.6
Bio boiler	5.6	15.2	15.2	5.9	18.1	18.1	1.2	29.6	24.0	1.2	30.9	27.8
Others	24.5	26.4	26.4	24.4	25.5	25.5	15.9	18.2	16.7	12.4	13.7	14.1
Total	44.8	44.8	44.8	45.8	46.3	46.3	47.9	48.1	48.0	49.5	49.5	49.5

[a] Energy policy of 1994 with extended support.

The total use of electricity is even somewhat higher under the 1994 policies. This is due to the fact that the subsidies for the different plants make electricity generation more cost effective and that the fee on CO_2 emissions reduces the cost effectiveness of individual oil burners for residential heating. Also, under the 1994 policies, district heating increases. This leads to decreased CO_2 emissions from the residential sector compared with those under the 1990 policy.

In contrast to CO_2 emissions from the residential sector, the CO_2 emissions from the industrial sector will rise because the changes in the tax system will strongly reduce the cost of fossil fuels for industrial use.

For the transportation sector there are no changes between the scenarios.

4. CONCLUSIONS

It has been shown how the energy system model Markal can be used to evaluate tax policies. The model is used to estimate both the realized effects of decided policy changes and the expected future effects of the policies.

The analysis shows that application of the energy policy of 1994 decreases CO_2 emissions compared with those achievable with the 1990 policy. However, for the different sectors the reductions in CO_2 emissions are not uniform. The emissions from the industrial sector and the electricity generation sector are rising, whereas those from the residential sector and from district heating are declining.

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POSSIBLE ROLE OF NUCLEAR POWER IN REDUCING ENVIRONMENTAL EMISSIONS FROM FUTURE ELECTRICITY GENERATION IN PAKISTAN

A.M. KHAN, A.I. JALAL,
A. MUMTAZ, G.R. ATHAR
Applied Systems Analysis Group,
Pakistan Atomic Energy Commission,
Islamabad, Pakistan

Abstract

POSSIBLE ROLE OF NUCLEAR POWER IN REDUCING ENVIRONMENTAL EMISSIONS FROM FUTURE ELECTRICITY GENERATION IN PAKISTAN.

The electricity demand in Pakistan is expected to increase very substantially in the coming decades because of the growing industrialization, the great pace of socioeconomic development and the rapid electrification of rural areas. Such an increased level of electricity generation is likely to result in serious environmental degradation due to the high levels of pollutant emissions from various types of power plants and their related fuel cycle facilities. The paper describes a study based on the DECADES methodology, involving the development of power generation expansion plans up to the year 2020, under two different scenarios — one envisaging a reasonable growth in nuclear power capacity and the other assuming a moratorium on nuclear power. The two cases are compared in terms of their associated environmental releases of pollutants such as SO_2, NO_x, CO_2, CH_4 and radioisotopes, taking into account the full fuel chains of each supply option. It is shown that increased use of nuclear power for electricity generation in Pakistan will not only be cost effective but will also help to reduce environmental degradation due to electricity generation activities in the country.

1. INTRODUCTION

In recent years, environmental concerns have received increasing attention in Pakistan. Among the various activities responsible for environmental degradation in the country, those related to energy production and consumption are believed to be by far the most damaging. The present consumption of primary commercial energy is about 35 million tonnes of oil equivalent (toe), of which about 85% is in the form of fossil fuels. The consumption of these fuels results in annual emissions of about 650 000 t SO_2, 300 000 t NO_x and 70 million t CO_2. Besides, large quantities of liquid and solid wastes are produced by the energy sector. In the energy sector, electricity generation is a major source of environmental pollution. Even though some 45% of electricity generation are based on hydro capacity, the power generation activities are responsible for about 30% of the pollutant releases from the use of fossil fuels. The present installed electricity generation capacity is about 12 500 MW. It has been projected that the capacity requirements will increase to a level of about 37 000 MW by the year 2010 and to about 78 000 MW by the year 2020. Such a large expansion of the power sector will, on the one hand, require very large capital investments and, on the other, result in considerable degradation of the country's environment, unless preventive measures are taken well in advance. The incorporation of environmental pollution abatement devices in fossil fuelled plants generally increases the initial investment costs for such facilities, but the investment costs for environment friendly technologies (solar, nuclear, hydro) are significantly higher. National planners are thus confronted with the task of formulating plans for electricity system expansion to meet future electricity needs, consistent with the financial resources of the country, while avoiding excessive environmental pollution.

This paper briefly reviews the historical development of the power sector in Pakistan and analyses various technological options for its future expansion. On the basis of an initial comparison of different options in terms of their economic and environmental impacts, two alternative expansion plans have been developed and their environmental implications analysed. The work is based on the research effort of the Applied Systems Analysis Group of the Pakistan Atomic Energy Commission under the IAEA co-ordinated research programme on case studies to assess and compare the potential role of nuclear power and other options in reducing emissions and residuals from electricity generation.

2. POWER SECTOR DEVELOPMENT

The consumption of energy in Pakistan at present comprises about two thirds in commercial form and one third in non-commercial form. Primary commercial energy consumption amounts to about 35 million toe per annum (oil 40%, gas 38%, coal 6%, hydro 15% and nuclear 0.4%). The present level of electricity generation is about 50 000 GW·h, comprising 44% hydro and 56% thermal (Fig. 1). Over the last 20 years the power generation capacity has increased from 2430 MW to about 12 500 MW, with the share of hydro capacity remaining in the range of 35–45%. The present installed capacity comprises about 38% hydro, 35% oil/gas steam, 9% combustion turbines, 16% combined cycle, 1% coal and 1% nuclear.

The consumption of electricity in Pakistan has increased at a rate of about 10% per annum over the last 20 years. However, at present, only 55% of the population has access to electricity. Electrification of rural areas is one of the high priority objectives of the Government. Furthermore, the increased emphasis on industrialization entails a substantial expansion in power generation capacity in the coming years. According to a recent study conducted by our group, using the IAEA MAED model, the future requirements of electricity will increase at about 8–9% per annum during

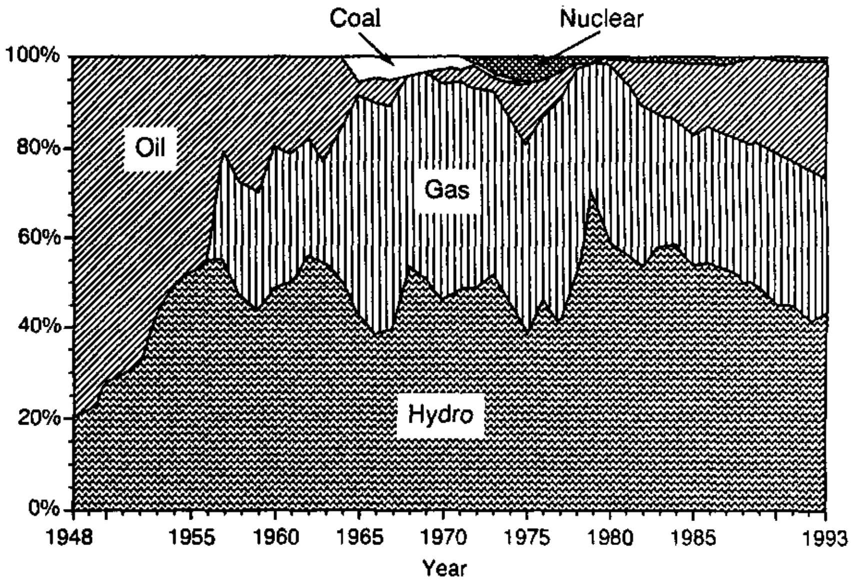

FIG. 1. Electricity generation mix in Pakistan for the period 1948–1993.

the next 25 years. The peak load has been estimated to increase from about 7600 MW in 1993 to about 29 000 MW by 2010 and to about 65 000 MW by 2020. To meet these requirements, very large capacity additions, at an amount of 70 000 to 75 000 MW, will have to be made during the next 25 years.

3. FUTURE SUPPLY OPTIONS

At present, Pakistan meets about one third of its total commercial energy needs or three quarters of its oil requirements through imports. The oil import bill has consumed about 25–30% of the export earnings in recent years. The dependence of Pakistan on energy imports, in spite of its very low level of per capita consumption, is due to its extremely low fossil fuel resources. The total proven fossil fuel reserves amount to only 680 million toe (or 6 toe per capita), comprising 407 million toe for gas, 28 million toe for oil and 245 million toe for coal. Recently, a large coal field was found at Thar in the Thar Parkar district of the Sind Province, with an estimated resource potential of over 150×10^9 tonnes in the form of lignite with about 1% sulphur content. The coal field still has to be investigated in detail for its reserves, mineability and quality of coal.

The future availability of indigenous fossil fuels for power generation will remain very limited. Natural gas, which at present provides about 30% of the power generation capacity, is already in short supply. Additional commitments of gas supply for power generation can only be made if new large gas fields are discovered. The proven coal reserves can hardly provide 1000 MW of power generation capacity. However, it is hoped that the recently discovered large coal field at Thar can be developed in the next 10–15 years to supply coal for 10 000 to 15 000 MW power generation capacity.

Although Pakistan is endowed with some 30 000 MW of hydropower potential, only about 15% of this potential has been exploited so far. Future development of hydropower is constrained by a combination of technoeconomic, environmental and sociopolitical factors. At present, hydropower facilities with a capacity of 1630 MW are under construction, while the construction of plants with about 1640 MW capacity is planned. In addition, construction of two large hydro projects with a total installed capacity of about 6000 MW is under consideration.

Nuclear power technology was introduced in Pakistan in 1971, when a 137 MW CANDU type plant was built. The plant has performed satisfactorily over the past 24 years (despite some difficulties regarding the supply of fuel and spare parts) and is now being refurbished in order to extend its life and to enhance its safety. A second nuclear power plant, a 300 MW PWR unit, is under construction at Chashma. It is envisaged that nuclear power generation will play a relatively more significant role in the coming decades.

In view of the limitations of indigenous energy resources, it is planned to import coal and natural gas. At present, three gas pipelines (with a capacity of 1–2 trillion ft^3/a each[1]) for imports from Iran, Qatar/Oman and Turkmenistan are under consideration. It is expected that one of these pipelines will be operational directly after the turn of the century. It is envisaged that a sizable fraction of the imported gas (up to about 50%) will be available for power generation. The use of imported coal for power generation will be an economic proposition only if the required facilities are located near the coast.

4. ECONOMIC AND ENVIRONMENTAL COMPARISON OF ELECTRICITY GENERATION OPTIONS AND EXPANSION PLANS

4.1. Methodology and approach

In view of the emerging importance of environmental and health related impacts of different energy systems, particularly those associated with the production

[1] 1 ft = 3.048×10^{-1} m.

of electricity, it has been felt for some time that it is necessary to formulate medium and long term national power system expansion plans which, besides being based on resource availability and technoeconomic aspects, will also give due consideration to the related environmental and health impacts. The inter-agency joint project on databases and methodologies for comparative assessment of different energy sources for electricity generation (DECADES), launched in 1993, has developed a methodology that aims at meeting the above objectives. The methodology provides for (i) the establishment of a country specific database (CSDB) covering the country specific technical, economic and environmental parameters of different electricity generation technologies in a convenient database format, and (ii) a set of tools to formulate optimal power system expansion plans under chosen sets of resource availability and other constraints and to assess the environmental impacts associated with the full fuel chains involved in these plans. The CSDBs developed for Pakistan and the DECPAC module of the DECADES software system have been used to formulate power system expansion plans for the present study. Because the environmental impact assessment module of the DECADES software was not available to us in the course of this study, the environmental emissions reported here have been worked out in a spread sheet outside the DECADES system using the fuel consumption of various plants obtained with the DECPAC module and the information on environmental parameters collected in the CSDB for Pakistan.

4.2. Cost-economic comparison of individual options

For initial screening of the different electricity generation options available in Pakistan, a cost-economic analysis of the major options (other than hydro) for base load generation was carried out. The technologies considered are: (i) a 300 MW steam plant using imported furnace oil, (ii) a 450 MW combined cycle plant based on natural gas, (iii) a 600 MW steam plant without flue-gas desulphurization (FGD) based on imported coal with 1% sulphur content, and (iv) a 600 MW PWR type nuclear power plant. All these technologies are proven and are either in use in Pakistan or under consideration for future expansion of the country's power system. The comparison was made using the technical and economic data collected for the CSDB for Pakistan. Two different values were used for the specific costs of nuclear power plants in order to cover their range of uncertainty. Table I gives an economic comparison of base load power generation options in Pakistan. The levelized cost of electricity generation was worked out using 5% and 10% discount rates (in real terms) and making two assumptions about future real escalations in fossil fuel prices: (i) the prices remain constant at the present level and (ii) the prices increase at 2% per annum. For simplicity, it was assumed that all plants will start operation in the year 1995. It is found that nuclear power is by and large the most attractive proposition in terms of the levelized cost of electricity generation. Among the fossil fuel powered plants, the combined cycle power plant using natural gas as fuel has definite

TABLE I. ECONOMIC COMPARISON OF SOME BASE LOAD POWER GENERATION OPTIONS IN PAKISTAN[a]

	Coal (without FGD)	Oil (HSFO)	Gas (combined cycle)	Nuclear (LWR)
Net overnight cost ($/kW)	1130	980	720	1700–2000
O&M cost (mills/kW·h)	3.5	3.5	2.0	5.4
Fuel cost (mills/kW·h)	22.5	24.9	24.1	4.8
Levelized generation cost (mills/kW·h)				
At 5% real discount rate	39.3–45.7[b]	39.7–46.8[b]	34.2–41.1[b]	28.2–31.4
At 10% real discount rate	50.2–55.0[b]	48.5–53.8[b]	40.2–45.4[b]	39.6–44.8

[a] Costs in 1992 US dollars.
[b] Assuming 2% escalation in fuel costs per annum.

Source: Based on Refs [1, 2].

economic advantages over other plants. Coal fired plants have about the same levelized cost of electricity generation as oil fired plants. The oil fired power generation capacity considered here is based on high sulphur furnace oil (HSFO) with 3.5% sulphur content. If the plant has an FGD facility or if the more expensive low sulphur furnace oil is used as fuel, the generation cost is estimated to increase by about 8–10%.

4.3. Environmental impact comparison of individual options

Table II lists the estimated emissions of major pollutants per GW·a of electricity generation from power plants alone and from the full fuel chains corresponding to each of the above mentioned electricity generation options in Pakistan. At present, the CSDB for Pakistan includes data on pollutant emissions for the following steps corresponding to different fuels: for indigenous coal: mining, cleaning/drying and electricity generation; for indigenous gas: extraction, processing, compression for transportation via pipelines and electricity generation; for imported oil: refining,

TABLE II. EMISSIONS OF MAJOR POLLUTANTS PER GW·a OF ELECTRICITY GENERATION FROM VARIOUS POWER GENERATION OPTIONS IN PAKISTAN

	Coal (without FGD)		Oil (HSFO)		Gas (combined cycle)		Nuclear (LWR)	
	Plant level	Full fuel chain	Plant level	Full fuel chain	Plant level	Full fuel chain	Plant level	Full fuel chain
Non-radioactive emissions (1000 t)								
SO_2	51.3	51.3	151.9	153.9	0.02	1.6	—	0.032
NO_x	31.8	31.8	28.8	29.5	13.2	18.7	—	0.009
Particulates	58.7	58.7	2.8	2.9	0.5	0.5	—	—
CO_2	7761.4	7761.4	6902.9	7257.2	5247.0	5437.2	—	70.0
CH_4 (expressed as GHG equivalent CO_2)[a]	—	n.a.	—	5.8	—	1223.3	—	—
Liquid waste	876.0	876.0	525.6	2790.9	350.0	351.0	—	0.025
Solid waste	528.0	528.2	—	12.5	—	—	—	0.037
Radioactive emissions (TBq)								
Kr-85 (air)	—	—	—	—	—	—	72.0	72.0
Xe-133 (air)	—	—	—	—	—	—	180.0	180.0
H-3 (air)	—	—	—	—	—	—	28.0	28.0
H-3 (water)	—	—	—	—	—	—	62.0	62.0
Other radionuclides	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	7.7	7.7

[a] 1 t of methane = 70 t of GHG equivalent CO_2.

Source: Based on Refs [1, 4, 5, 6].

transportation and electricity generation; for imported coal: electricity generation; for imported gas: compression and electricity generation; for nuclear: fuel fabrication and electricity generation (it is assumed that the other steps of the nuclear fuel cycle will not be undertaken in Pakistan to any significant extent). It is seen that with respect to non-radioactive emissions, nuclear power is the cleanest technology among all options considered here. On the plant level, there are no emissions of SO_2, NO_x or greenhouse gases (GHG). Although small quantities of these gases are released from the full fuel chain, they are insignificant compared with those emitted in the case of power generation based on fossil fuels. Among the fossil fuel based power plants, natural gas fired combined cycle power plants have the cleanest technology. There are very small emissions of SO_2 and the emissions of NO_x and GHG are also smaller than those from oil and coal fired plants. By far the most polluting technology, both on the plant level and regarding the full fuel chain, is the coal based power generation. Besides large atmospheric emissions of pollutants, very large quantities of liquid and solid wastes are produced. In Table II, radioactive emissions are given only for nuclear power plants. It was not possible to estimate such emissions for fossil fuel based power generation because of lack of data. It should, however, be mentioned that a significant amount of radioactivity is released during coal mining, as well as during combustion of coal, oil or gas in fossil fuel based power plants. The health impacts of such emissions per GW·a of electricity generation from coal and oil based plants have been estimated [3] to be comparable with those from nuclear power plants, while those from gas based plants are an order of magnitude smaller.

4.4. Expansion plans for alternative power systems

In the case of Pakistan, all the above options would be required for an expansion of the power system in view of the limited indigenous fossil fuel and hydro resources, the constraints on the development of nuclear power and the need for diversification of the supply system. Thus, two alternative scenarios (Case 1 and Case 2) for the overall power system expansion for the next 25 years have been worked out with the help of the DECPAC module of the DECADES system. Basically, the two cases differ in terms of the extent of nuclear power capacity for future expansion. For Case 1, it is assumed that the present plans for nuclear power capacity addition will be implemented, which would result in the construction of nuclear power plants with a capacity of about 10 000 MW by the year 2020. For Case 2, a moratorium on the construction of new nuclear power plants is assumed. Keeping in view the limited indigenous energy resources and the constraints on their development, and also the proposed plans for the import of natural gas, programmes were worked out for capacity additions in hydroelectric plants, thermal power plants based on indigenous coal, and thermal power plants based on imported natural gas; these programmes are essentially identical in the two cases. The envisaged capacity

TABLE III. FUTURE ELECTRICITY GENERATION CAPACITY MIX (MW)

	1995	2000		2010		2020	
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Hydro	4 825 (38.7%)	5 318 (33.1%)	5 318 (32.7%)	9 808 (27.0%)	9 808 (26.8%)	14 704 (18.8%)	14 704 (18.8%)
Gas	3 973 (31.9%)	4 700 (29.2%)	4 700 (28.9%)	10 584 (29.1%)	11 484 (31.3%)	21 066 (26.9%)	21 366 (27.3%)
Oil	3 484 (27.9%)	5 413 (33.6%)	5 573 (34.3%)	5 413 (14.9%)	5 413 (14.8%)	14 632 (18.7%)	18 532 (23.7%)
Coal	115 (0.9%)	262 (1.6%)	262 (1.6%)	6 550 (18.0%)	9 550 (26.0%)	16 750 (21.4%)	23 350 (29.8%)
Nuclear	70 (0.6%)	395 (2.5%)	395 (2.5%)	3 995 (11.0%)	395 (1.1%)	11 125 (14.2%)	325 (0.4%)
Total	12 467	16 088	16 248	36 350	36 650	78 277	78 277

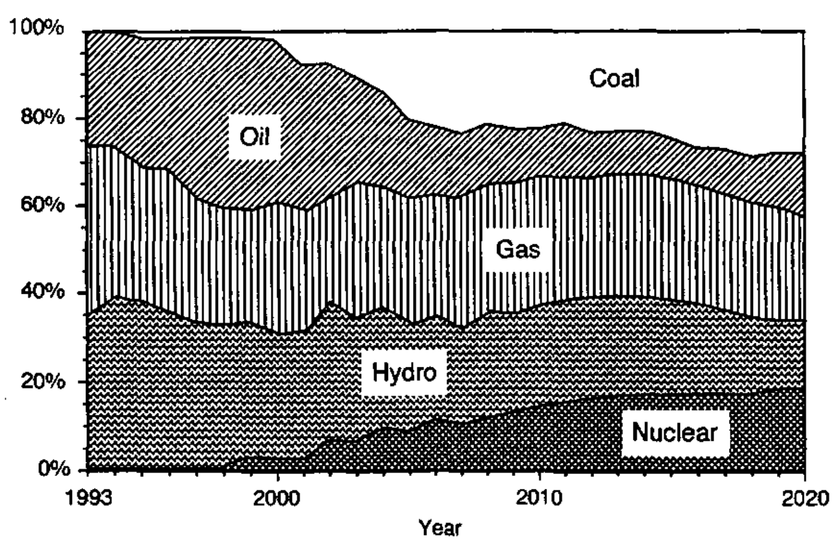

FIG. 2. Future electricity generation capacity mix in Pakistan (Case 1).

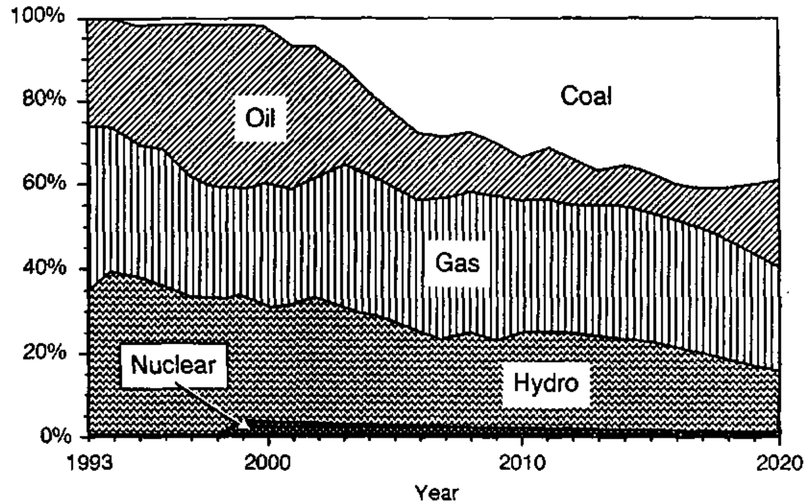

FIG. 3. Future electricity generation capacity mix in Pakistan (Case 2).

additions for 1995-2020 are: 9400 MW in hydropower plants; 1000 MW in coal fired fluidized bed combustion type plants based on indigenous Lakhra coal containing 4–6% sulphur; and about 16 500 MW in combined cycle plus gas turbine plants based on imported gas. It is assumed that, in each case, coal fired plants based initially on imported coal will later gradually shift to the use of indigenous Thar coal, to the extent of 10 000 MW by the year 2010 and 15 000 MW by the year 2020.

The total installed capacity required to meet the projected demand will be about 78 000 MW by the year 2020, compared with the present 12 500 MW. Table III and Figs 2 and 3 show the future electricity generation capacity mix for the two cases. In both cases the share of hydropower of the total installed capacity will decrease from 39% in 1995 to about 19% by the year 2020; the share of natural gas of the total installed capacity will remain at a level of 27–32% for the entire period. In Case 1, the share of nuclear power of the total installed capacity will increase gradually from about 1% in 1995 to about 14% by the year 2020. The oil and coal based capacities in Case 1 are 19% and 21%, respectively, by the year 2020. Since a moratorium on nuclear power development is assumed in Case 2, the corresponding shares of oil and coal based capacities are higher than those in Case 1. The share of oil fired plants by the year 2020 in Case 2 is about 24%, while the share of coal fired plants is about 30%. In Case 1, non-fossil fuel sources (hydro and nuclear) will contribute about 35–40% to the total electricity generation over the entire period, whereas in Case 2 the corresponding contribution will decline from the present level of about 40% to about 17% by the year 2020.

TABLE IV. ESTIMATED ANNUAL ENVIRONMENTAL EMISSIONS FROM ELECTRICITY GENERATION IN PAKISTAN

	1993	2010		2020	
		Case 1	Case 2	Case 1	Case 2
SO_2 (1000 t)	217	612	714	1774	2540
NO_x (1000 t)	84	297	380	770	1035
GHGs (million t of CO_2 equiv.)	34	116	146	274	342
Particulates (1000 t)	11	270	410	769	1091
Liquid waste (million t)	11	43	53	113	141
Solid waste (million t)	0	35	41	69	78
Atmospheric release of radioactivity[a]					
Kr-85 (TBq/a)	0	228	19	645	19
Xe-131 (TBq/a)	0	569	47	1613	47
H-3 (TBq/a)	31	119	38	251	7
H-3 in water (TBq/a)	68	264	84	556	16
Other radionuclides (TBq/a)	0.5	25	2.4	69	1.9

[a] Radioactive releases from fossil fuel based chains are not accounted for.

4.4.1. *Investment requirements*

The total investments required to build the additional plants are estimated at US \$99 $\times$ 10^9 for Case 1 and about US \$87 $\times$ 10^9 for Case 2. The extra cost for building the plants in Case 1 (which includes nuclear power plants) will be more than offset by the savings in the total operation cost of the system over the period 1995–2020 compared with that for Case 2. The total operation cost is US \$131 $\times$ 10^9 for Case 1, compared with US \$146 $\times$ 10^9 for Case 2.

4.4.2. *Environmental emissions*

Table IV gives the annual environmental emissions from electricity generation in the years 1993, 2010 and 2020, for the two cases, estimated on the basis of analyses of the full fuel chains. Note that the emissions of all pollutants, except radioactivity, are higher in Case 2 than in Case 1. By the year 2020, the SO_2 and NO_x emissions, which give rise to acid rain, are 34–43% higher in Case 2 than in Case 1, while the GHG emissions are about 25% higher. Other pollutants, e.g. particulates, solid and liquid wastes, which are important only for the local environment, are also higher by about 15–40% in Case 2 than in Case 1. The radioactive emissions are higher in Case 1 than in Case 2, but this is mainly due to the fact that these emissions were considered in the present analysis only for nuclear power plants and that a moratorium on nuclear power is asumed in Case 2. However, the radioactive emissions from the envisaged level of nuclear power plants in Case 1 are not likely to pose any threat to the environment because such emissions from nuclear power plants and their related facilities are kept below the permissible limits for each site and because the average radiation dose from nuclear power production, even to typically exposed individuals, is only 1–2% of the dose from the natural background [3]. Regarding environmental impacts, the power system expansion plan in Case 1 is, therefore, superior to that in Case 2.

5. CONCLUSIONS

In view of the limited indigenous energy resources of Pakistan, all available technological options will have to be used for the planned expansion of the country's power system in the coming decades. Whatever the mix of different sources chosen for future electricity generation, the environmental emissions from the electric sector will increase by an order of magnitude over the next 25 years. However, the use of nuclear power can help to reduce significantly future environmental emissions of SO_2, NO_x, CO_2 and other pollutants, while radioactive releases will not pose a significant threat to the environment. Although the inclusion of nuclear power in the future electricity mix of Pakistan will result in somewhat higher investment costs, these will be more than offset by the corresponding reduction in the system operating costs. Further, the use of nuclear power will make the electricity generation system less vulnerable to future increases in fuel prices. It is thus clear that increased use of nuclear technology for electricity generation in Pakistan in the coming decades will not only be cost effective and desirable as regards security of supply but will also be very helpful in reducing environmental degradation due to future power generation activities in the country.

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COMPARATIVE ASSESSMENT OF ALTERNATIVE ELECTRICITY SUPPLY STRATEGIES IN ROMANIA
Results of a case study carried out using the DECADES computer tools

A. POPESCU, D. POPOVICI, F. BREAZU, M. POPESCU
Institute of Power Studies and Design,
Bucharest, Romania

Abstract

COMPARATIVE ASSESSMENT OF ALTERNATIVE ELECTRICITY SUPPLY STRATEGIES IN ROMANIA: RESULTS OF A CASE STUDY CARRIED OUT USING THE DECADES COMPUTER TOOLS.

There will be a significant growth of the electricity demand in Romania over the period 2005–2015; therefore, it will be necessary to devise an optimized strategy for electricity generation in order to ensure the economic development of the country and to achieve a standard of living that is similar to that of people in western European countries. For the development of electricity generation capacities in Romania it will be necessary to consider the security of supply of primary energies as well as the prospects of utilizing clean technologies in order to fulfil the requirements for environmental protection. In view of the medium and long term forecasts of the electricity demand in Romania, it is expected that the import of fuels will increase. Therefore, it is very important to make comprehensive comparative assessments of different energy chains for electricity generation, incorporating health and environmental issues in the planning and decision making process. Since 1994, Romania has participated in the DECADES project and has used the DECPAC software to work out a country specific database. It was found that the 'least cost' development programme of power plants comprises new plants equipped with 660 MW combined cycle natural gas units. All expansion options and the fuel price escalation on the international market were taken into account. The nuclear power alternative is attractive as regards environmental protection and because it is not possible for Romania to secure the necessary gas supply.

1. INTRODUCTION

The large changes that are taking place in Romania and the envisaged transition from a planned, centralized economy to a market economy as well as Romania's integration into the European Union make it necessary to adopt proper strategies for the reorganization and development of the energy sector, taking into account economic, social, health and environmental aspects.

Such strategies cannot be adopted without the use of analysis methods that permit an even better appraisal of both the economic and the environmental aspects of technological alternatives for electricity generation. Therefore, the ENPEP package programs [1] were implemented in Romania after 1990, with the assistance of the IAEA. This enabled integrated planning of the use of resources, thus providing least cost development strategies for power plants, with consideration of user specific constraints.

The Romanian energy sector includes a large variety of technologies because Romania has multiple primary energy resources (coal, crude oil, natural gas, uranium, hydropower, as well as geothermal, solar and biomass energy sources), which are, however, limited.

The quantities of energy resources in Romania were not large enough to cover the increasing energy demand, and therefore fuel imports have grown continuously since 1984. Taking into consideration the medium and long term forecasts, it is expected that fuel imports will still increase. Under these conditions, it is very important to make comprehensive comparative assessments of different energy chains for electricity generation, incorporating health and environmental issues in the planning and decision making process. To achieve these goals, it is necessary to create a Romanian specific database with relevant information on technical and economic characteristics and on the health/environmental aspects of technologies in the fuel chains for electricity generation.

In 1994, Romania was allowed to participate in the DECADES project, since it had the necessary support to work out a country specific database (CSDB) and the opportunity to utilize the DECPAC software [2]. The access to software for the DECADES project allowed a comparative assessment of the fuel chain (from fuel extraction to waste storage) to be performed in the decision making process regarding the energy sector, since this software provides the necessary complex data.

Within the DECADES project, Romania has performed a case study that deals with the comparative assessment of alternative strategies for electricity supply.

2. OBJECTIVE AND SCOPE OF THE CASE STUDY

The objective of the case study is the establishment of an optimized long term strategy for electricity generation capacities in Romania up to the year 2015, taking into account economic competitiveness, security of fuel supply, participation of the Romanian industry in manufacturing equipment for new power plants, as well as health and environmental aspects.

On the basis of the latest forecast of the technological and socioeconomic development, a basic evolution scenario for the electricity demand up to the year 2015 was established by means of the MAED model. Taking into consideration the assumptions, constraints and development options for new electricity generation capacities, based on the reference technology database (RTDB) and the CSDB, elaborated in the framework of the DECADES project, and using DECPAC ELECSAM (electric system analysis module), the new planning programme for electricity generation capacities in Romania was established. This programme should lead to minimum capital and operation costs of power plants for the entire study period.

The same method was used for determining the expansion programme of alternative electricity generation capacities, based on nuclear plants equipped with 700 MW units and PHWR reactors of the CANDU type.

Sensitivity analyses of the obtained results were performed in order to examine the effects of a change of some key parameters on the 'least cost' programme and to determine the robustness of this programme. The key variables taken into account were the price of natural gas, the discount rate and the capital cost for commissioning new plants.

The air pollutant emissions (CO_2, NO_x and SO_x) have been established for all plant alternatives (existing plants and new ones), for each year of the period 1995–2015, on the basis of the methodology of the DECPAC model. The case study considers the fuel chains for coal, natural uranium and fuel oil, from extraction, transport and processing to waste storage (see Fig. 1), including both economic aspects and the environmental impact.

Finally, the expansion strategies for electricity generation capacities will be compared on the basis of a multicriteria analysis, including the safety of fuel supply, economic results, and environmental and health aspects.

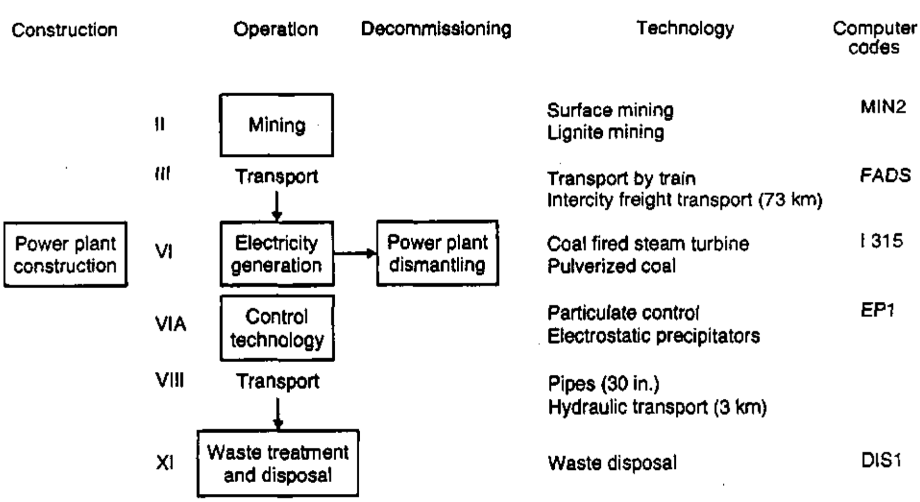

FIG. 1. Solid fuel: lignite chain.

3. DESCRIPTION OF SCENARIOS

The establishment of the scenarios considered in the comparative analyses of alternative strategies for developing electricity generation capacities is based on Romania's present situation. The socioeconomic changes that occurred in Romania after 1989 had a strong impact on the expansion of the power sector.

The evolution of the demand for electricity and heat after 1989 greatly changed the structure of supply and consumption. Between 1980 and 1989, the domestic electricity production was not sufficient to meet the demand; therefore it was necessary to import electricity to a greater extent. When electricity consumption decreased, the imports were reduced, and the installed capacity in the Romanian electricity system as well as the available primary energy sources were utilized.

The existing electricity generation facilities in operation by the end of 1994 demonstrated the national policy of using combined electricity and heat generation (cogeneration); this provided about 60% of the heat supply in 1994 through district heating systems. By the end of 1994, the total installed capacity of power plants connected to the national electricity network was 20 027 MW, 29% of which was in hydropower plants and 71% in thermal power plants. Romania has over 70 thermal power plants with an installed capacity of 14 220 MW, of which 7703 MW (54%) are in coal fired plants. The capacity of condensation plants represents about 81% of that of coal fired plants and about 40% of that of hydrocarbon fired plants.

The analyses of the evolution of existing power plants in Romania led to the following conclusions:

(a) Rehabilitation of certain existing units instead of commissioning of new units will lead to a decrease in the capital costs required for development of electricity generation capacities in the next 15–20 years.

(b) Rehabilitation of plant units will have a favourable influence on both the energy balance and the quality of the environment.

(c) Cogeneration power plants will undergo rehabilitation; later, they will be developed in compliance with the heat demand.

(d) For power plant units under various phases of construction it was decided to provide a capacity of 1600 MW under very advanced performance conditions, e.g. 1 × 700 MW in nuclear power plants, 350 MW in hydropower plants and 550 MW in thermal power plants.

With a view to meeting the electricity demand in Romania (see Fig. 2), the following two possibilities were considered: continuation of the construction work of plants at various stages of completion, and building of new plants.

Romania has an installed capacity of 3750 MW in power plants that are at various stages of construction; these 'candidate plants' are the nuclear power plant

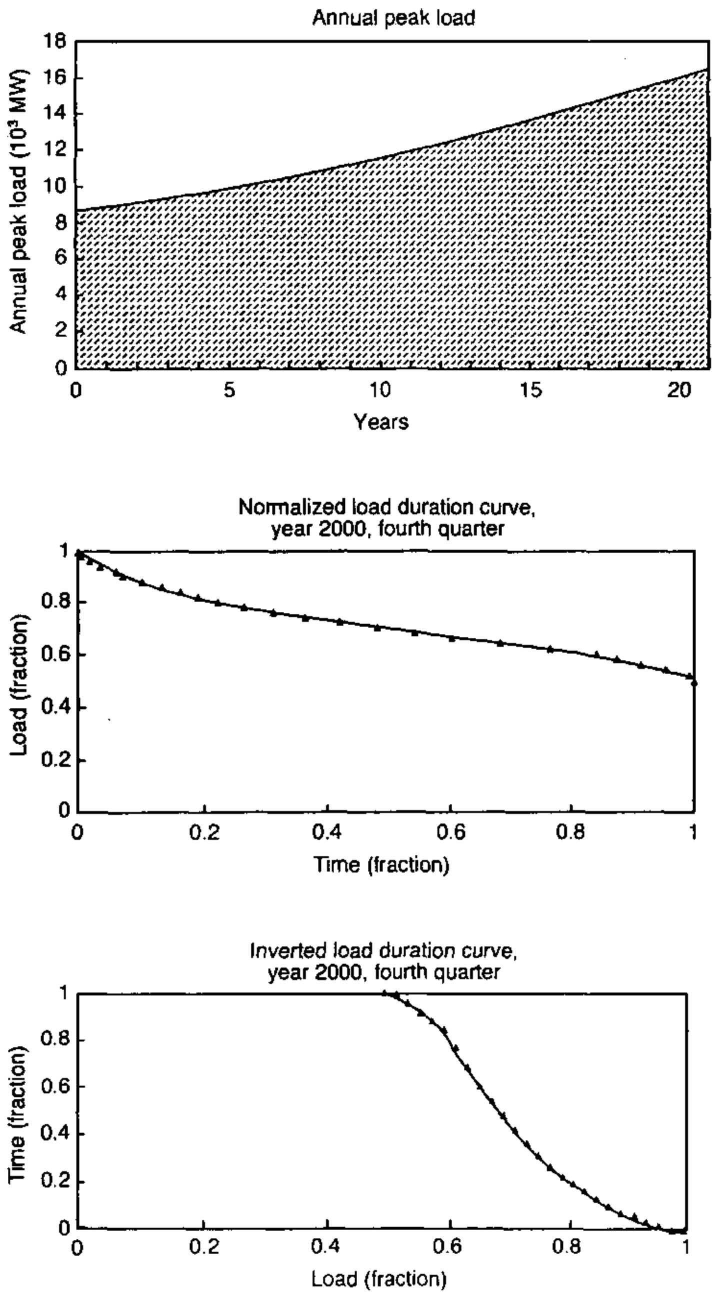

FIG. 2. Data for the electricity demand in Romania.

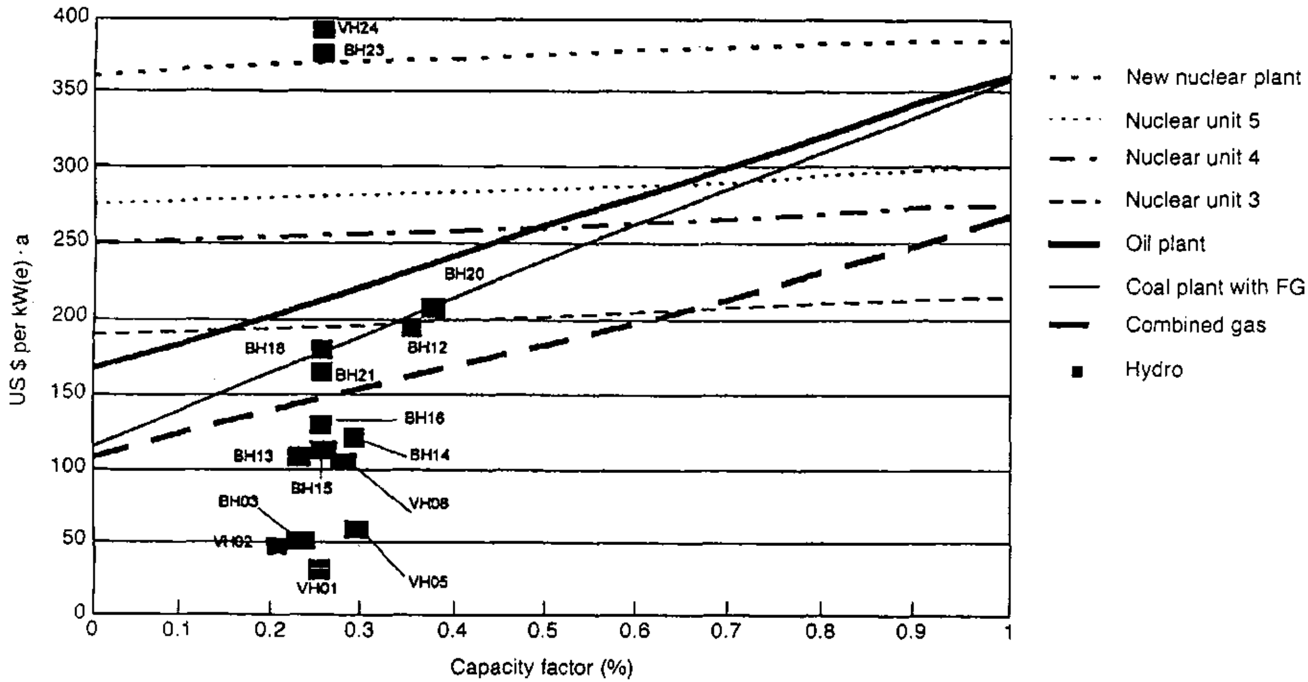

FIG. 3. Ranking of candidate power plants (screening curves).

at Cernavodă, with a total capacity of 2800 MW (4 × 700 MW), and hydropower plants with 950 MW.

As new power plants, the following types of units are considered in the study:

— 700 MW units, coal fired, provided with fluidized gas desulphurization;
— 700 MW units, fired with fuel oil with a sulphur content of below 1%;
— 660 MW units of the gas fired combined cycle type;
— Nuclear power plants equipped with CANDU type reactors and 700 MW units;
— Hydropower plants.

Figure 3 shows the ranking of the candidate plants.

In order to cover the electricity demand up to the year 2015, two alternative scenarios for new power plants were analysed, namely: (1) development of plants with least capital and operation costs; this option is called 'least cost alternative'; and (2) use of nuclear units to cover the demand for new capacity; this option is called 'NPP alternative'.

4. ANALYSES CARRIED OUT

The economic analyses performed led to the following conclusions:

(a) The lowest value of the objective function is obtained by installation of new plants equipped with 660 MW combined cycle natural gas units. For the 'NPP alternative' the value of the objective function is higher (2.6%).
(b) The lowest capital cost is achieved by the 'least cost alternative'; for the 'NPP alternative' the capital cost is higher by 170%.
(c) For new plants the analysis results are presented in Figs 4 and 5:
  — In the 'least cost alternative' the planned capacities are achieved by 9 × 660 MW combined cycle gas turbine units, for which an additional import of natural gas of 10×10^9 m^3 per year is required for electricity generation by the year 2015.
  — In the 'least cost alternative' the fossil fuel requirement for electricity generation by the year 2015 is three times higher than that in the 'NPP alternative' (Figs 6 and 7).

The sensitivity analyses of the 'least cost alternative' with variation of certain economic parameters led to the following conclusions:

(a) The increase in the natural gas price (by up to 1.8 times) during the study period will not lead to a withdrawal of combined cycle gas fired plants from the optimal solution.

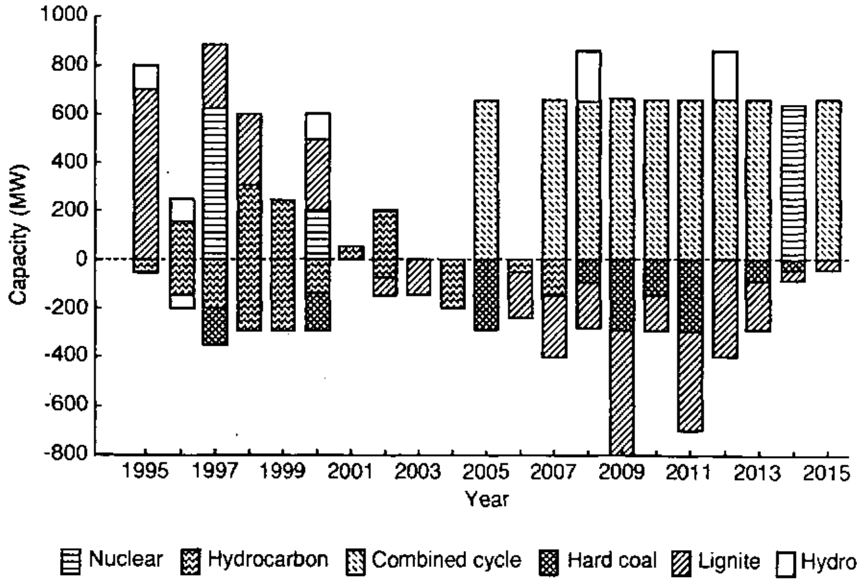

FIG. 4. Capacity added in the 'least cost alternative'.

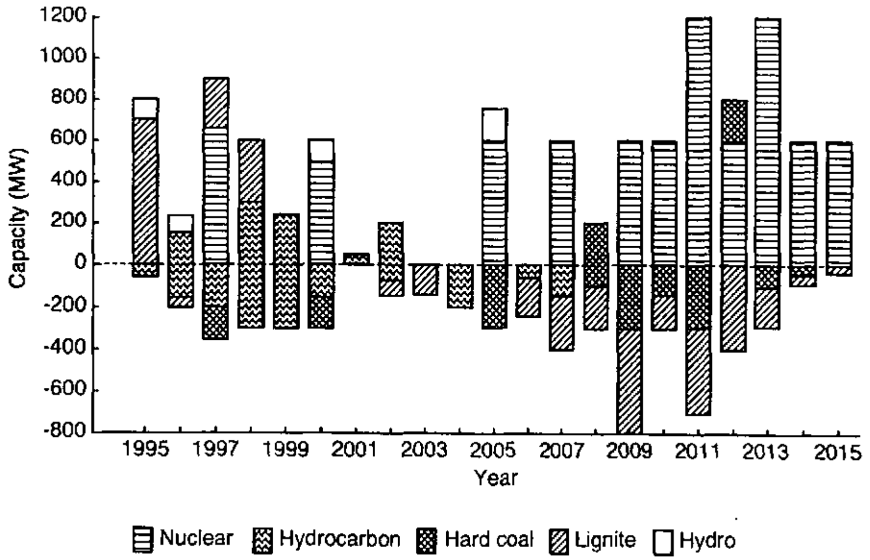

FIG. 5. Capacity added in the 'NPP alternative'.

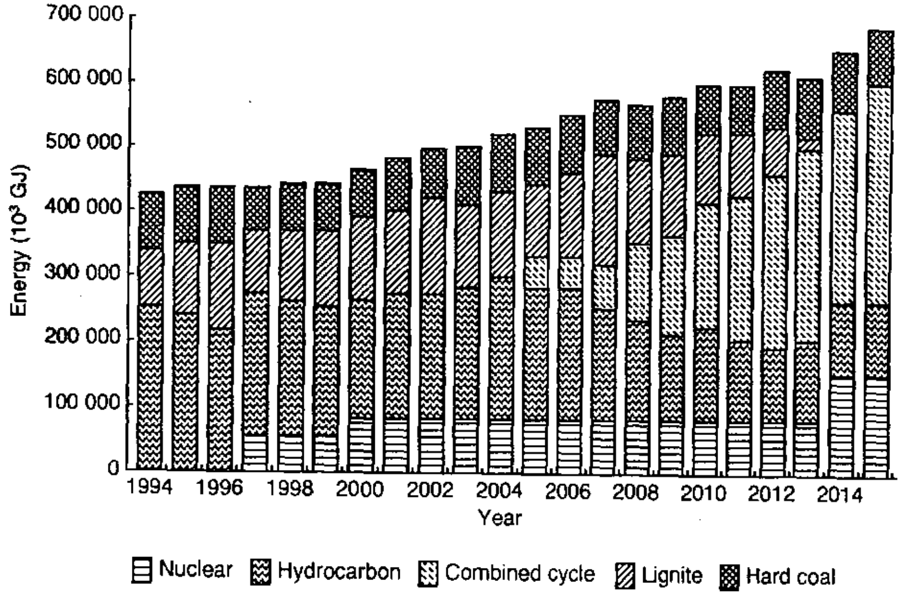

FIG. 6. Fuel consumption in the 'least cost alternative'.

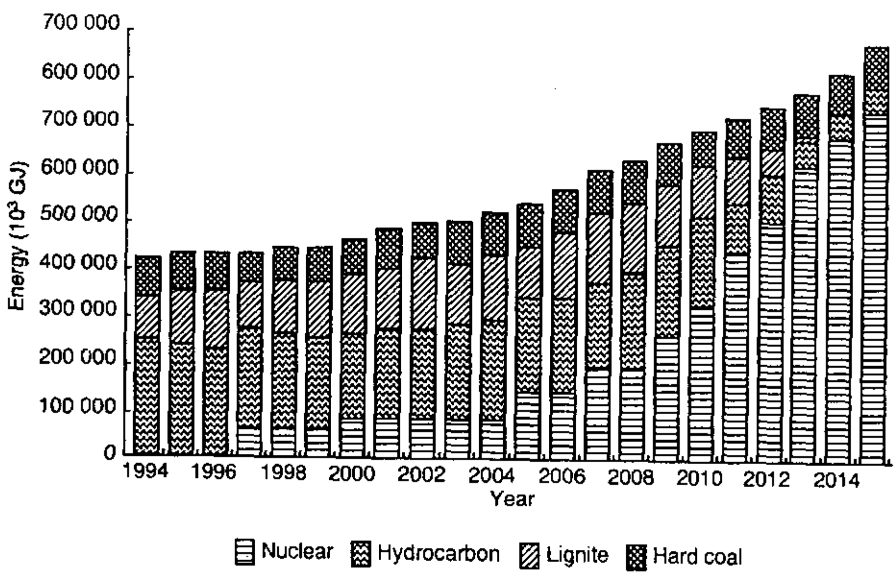

FIG. 7. Fuel consumption in the 'NPP alternative'.

(b) Discount rates of 7% and 15%, as envisaged for the optimal solution (10% in the base case), will bring about slight changes in the commissioning sequences of some units, but will not modify the optimal solution.

(c) The increase in investment costs (by 35%) for gas fired combined cycle units will not change the structure of the 'least cost alternative'.

The analyses of air pollution emissions for the two scenarios led to the following conclusions:

(a) The 'NPP alternative' will lead to a reduction of NO_x emissions by 70% and of CO_2 emissions by 80% by the year 2015, compared with those achieved with the 'least cost alternative'.

(b) Comparing the level of air pollutant emissions from power plants in 1989 with that intended for the year 2015, it is estimated that a reduction of NO_x emissions by 60% and of CO_2 emissions by 40% will be achieved with the 'least cost alternative'. A reduction of NO_x emissions by 180% and of CO_2 emissions by 160% will be achieved with the 'NPP alternative'.

5. CONCLUSIONS

The case study performed in Romania within the DECADES project, using the software of this project, has shown that the 'least cost' development programme of power plants will include new power plants equipped with 660 MW combined cycle natural gas units, taking into consideration all expansion options and the fuel price escalation on the international market, in agreement with the World Bank forecast of May 1994. This programme has a negative impact on the environment compared with the nuclear programme, which will lead to a decrease of NO_x and CO_2 emissions by 40% and 44%, respectively.

The nuclear alternative would be more attractive if the specific investments for nuclear units could be reduced by about 20% or if the natural gas price would increase to about twice the one envisaged in the analysis.

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ECONOMIC AND ENVIRONMENTAL IMPLICATIONS OF INCORPORATING CO_2 ABATEMENT POLICY MEASURES INTO THE INDIAN POWER SYSTEM
A modelling approach

A. DAS
Tata Energy Research Institute,
New Delhi, India

Abstract

ECONOMIC AND ENVIRONMENTAL IMPLICATIONS OF INCORPORATING CO_2 ABATEMENT POLICY MEASURES INTO THE INDIAN POWER SYSTEM: A MODELLING APPROACH.

The Indian power system is dominated by coal based capacity (64% of the total capacity). India has a large potential of hydro and renewable energy sources, but the absence of an appropriate national policy to develop cleaner technologies leads to adverse impacts of electricity generation on the environment. The power sector is the single largest contributor of CO_2 in India. If the current expansion of power generation based on coal continues, the Indian power system, which is expected to grow at 6–7% per year in order to fulfil the rising demand, will pose a serious threat to the environment in the coming years. The paper examines the economic and environmental implications of introducing measures for the reduction of CO_2 emissions, such as an accelerated development of the hydro potential, and a larger penetration of renewable energy and clean coal technologies for the future expansion of the domestic power system. A mathematical model was developed in the framework of linear programming, to derive the optimal way of capacity expansion for the Indian power system, together with a study of the costs and emissions under different scenarios. The business-as-usual scenario extrapolates the past trend to the future development of the power system, with possible improvements such as the use of imported gas and coal for power generation. Other scenarios assume the introduction of CO_2 abatement measures. The study has been performed for a time horizon of 20 years, beginning with 1991/1992. Finally, the paper gives some recommendations regarding policies that would lead the country to environmentally benign power development.

1. INTRODUCTION

The Indian power system is dominated by coal based capacity. Coal has a share of nearly 64% of the total capacity of 72 300 MW (1992/1993) and contributes 70% to the total power generation. Over the period 1970–1992, the share of small hydropower plants in the total capacity has declined from 43 to 27%. In spite of having a large potential of hydro and renewable energy sources, the country continues to add coal based capacity to a large extent. The absence of an appropriate national policy to develop cleaner power sources leads to adverse effects of electricity generation on the environment.

The power sector is the single largest contributor of CO_2 in India. If the current expansion of power generation based on coal continues, the Indian power system, which is expected to grow at 6–7% per year in order to fulfil the rising demand, will pose a serious threat to the environment in the coming years.

The paper examines the economic and environmental implications of introducing measures for the reduction of CO_2 emissions, such as an accelerated development of the hydro potential, and a larger penetration of renewable energy and clean coal technologies for the future expansion of the domestic power system.

Different scenarios were analysed in order to assess the potential reduction of mainly CO_2 emissions from the power system and the associated cost. The 'business-as-usual' scenario was developed on the basis of past trends, but a number of environmentally benign measures were considered in the abatement scenarios.

2. METHODOLOGY

A mathematical model was developed in the framework of linear programming, which was used to derive the optimal way of capacity expansion for the Indian power system. In India, there is large regional variation in energy demand and in the availability of resources for power generation. For example, coal fields are situated in the eastern part of the country, while nearly 60% of the unexploited hydro potential is located in the northern and north-eastern parts. The Central Electricity Authority (CEA) has divided the country into five regions in order to perform a planning exercise.

Because of this, the model was developed at a regional level, for the regions defined by the CEA. GAMS software was used for the model. Since the model is a static one, it was developed for the years 2001/2002, 2006/2007 and 2010/2011 (these are the terminal years of the 9th, 10th and 11th Five Year Plans of the Government of India). The projection of electricity demand of consumers for these years was made at a regional level, using the regression technique. Taking this regional demand for electric energy by consumers as being exogenous, the present value of the electricity system cost, comprising the capital cost of adding new capacity (generation as well as transmission and distribution), the fixed cost of operation and maintenance and the fuel cost are minimized in the model. For all of these costs, 1993/1994 prices are used in the model. The model allows for inter-regional transfer of power by assuming the existence of a national grid.

3. SCENARIOS

The model was used to develop several scenarios. The business-as-usual (BAU) scenario considers past trends in the development of the power sector, together with expected changes (such as use of imported gas for power generation). Alternative scenarios incorporate measures for reducing CO_2 emissions in the Indian power system. The BAU scenario was developed for the years 2001/2002, 2006/2007 and 2011/2012; the alternative scenarios were developed only for the year 2011, because a considerably longer time horizon is required for measures having a significant impact on CO_2 emissions. The different scenarios are described below.

3.1. Business-as-usual scenario

In this scenario, the electricity demand at a regional level was estimated by applying the regression technique, and this demand was used in the model. For a projection of the electricity demand, the increase in the gross domestic product (GDP) was taken to be 5.6% for the period 1992–1997, 6.05% for the period 1997–2002 and 6.5% for the time beyond the year 2002. These are the growth rates provided by the Ministry of Planning for the 8th, 9th and 10th Five Year Plan, respectively. For the time frame of the analysis, a number of improvements of various technical parameters were assumed, i.e. for the system load factor, the transmission and distribution losses of the power system, the plant load factor, auxiliary losses and the thermal efficiency of plants.

The domestic gas production in the country was projected at 30×10^9 m^3 by the Ministry of Planning for the year 1996/1997, which is the terminal year of the 8th Five Year Plan. The Government of India allocated 9×10^9 m^3 of domestic gas production to the power sector for the year 1996/1997. In a study carried out recently by the Ministry of Petroleum and Natural Gas it was pointed out that because of India's inadequate gas reserves it is unlikely that the domestic gas production in future will increase by more than the amount projected in the 8th Five Year Plan. At present, no other assessment of gas production and of the allocation to the power sector beyond 1996/1997 is available. Therefore, in the present study it is assumed that the allocation of gas from domestic sources to the power sector for the year 2001 and the following years will be the same as that made for 1996/1997.

The nuclear power programme in India started in the 1970s. So far, the country was able to add only 2000 MW of capacity. Problems with imported technologies and difficulties in the development of indigenous technologies may be the main reasons for the failure to add more capacity. The performance of the existing plants is far from satisfactory, mainly because of operational problems. However, the Government of India is planning to add a capacity of 8000 MW by the year 2006/2007. On the basis of past experience with nuclear power installation and generation, the upper limits on nuclear capacity to be achieved in the milestone years under consideration are taken as 5000 MW, 8000 MW and 12 000 MW, respectively. The country has a hydro potential of 84 000 MW (as estimated by the CEA at a plant load factor (PLF) of 60%), of which only 20 000 MW has been exploited so far. In the period 1970–1992, the average capacity addition was 640 MW per annum. In the period 1987–1992, the average capacity addition was only 460 MW per annum. The main problems in connection with the development of hydro potentials are difficulties regarding the sharing of water resources by different States, environmental problems, rehabilitation of people affected by development projects in remote and geologically unstable areas, etc. In the present study, using a time trend analysis of the hydro capacity (data for the period 1980–1992), upper limits on the capacity of 27 000 MW, 30 800 MW and 34 700 MW have been imposed for 2001/2002, 2006/2007 and 2011/2012, respectively.

India is endowed with renewable energy sources. The importance of renewable energy to meet demands at decentralized locations has been clear for a long time. Under the Strategy and Action Plan of 1993, the Ministry of Non-conventional Energy Sources is consolidating and strengthening technology development and commercialization by providing market orientation and creating a favourable background for policy decisions. The present aim is to generate 2000 MW of power from renewable energy sources by the year 1997. Financial and fiscal incentives are offered to attract private investment. At present, two technologies, namely use of wind power and of hydropower from small plants (up to 15 MW), are at a mature stage so that they can be used for commercial production of electricity. The potential of these hydro plants and of wind power generators was assessed by the Ministry of Non-conventional Energy Sources as being of the order of 10 000 MW and 20 000 MW, respectively. In the BAU scenario, it was assumed that 5000 MW of wind capacity and 2500 MW of small hydro plant capacity may be achievable by the year 2011 if the present thrust on promotion of these two technologies continues.

India has abundant coal reserves, which will last for more than 250 years at the current rate of production. Nearly 70% of the coal reserves are located in the three eastern States (West Bengal, Bihar and Orissa) and 20% are located in one State of the western region (Madhya Pradesh). Thus, transportation of coal over large distances will be required. Moreover, the quality of nearly 73% of the coal reserves is inferior, since it has a low calorific value and a large ash content. The ash content of coal is increasing because of the high rate of open cast mining. Indian power plants are supplied with F-grade coal, which has a calorific value of 3500–4000 kcal per kilogram and an ash content of 35–45%. This leads to a lower thermal conversion efficiency, higher outage rates of plants, higher transportation costs for coal, which are due to the large amount of dirt that has to be transported together with the coal, and environmental problems related to ash disposal, CO_2 emissions, etc.

In the 1980s, the production of non-coking coal (mainly used for power generation) in India had grown at a rate of 7% per annum. Currently, about 76% of the non-coking coal produced in the country is being used for power generation.

To work out the future availability of coal for the power sector, a 6% growth rate of coal production was used in the present study and it was assumed that 80% of the coal produced in India would be used by the power sector. According to these assumptions, the availability of coal for power generation was estimated at (260, 349 and 467) $\times 10^6$ t for the years 2001/2002, 2006/2007 and 2011/2012, respectively.

The BAU scenario also considers the import of natural gas. The gas reserves in India as of April 1994 were 706×10^9 m^3. These reserves will last for 40 years at the current rate of gas production; this is much less than the required amount. The demand for natural gas in the country as fuel and feedstock is around 90×10^9 m^3. Realizing the importance of natural gas supply for the Indian energy sector and, at the same time, considering the shortfall in domestic supply, the Government of India is examining the feasibility of importing gas from countries such as Oman, Iran and Qatar. For the BAU scenario it was assumed that by the year 2001/2002, 5×10^9 m^3 of gas will be made available to the power sector through import, over and above the domestic supply, and 10×10^9 m^3 for the year 2006/2007 and the following years. The landfall price of imported gas was taken as US \$3.0 per million Btu.[1]

Further, the possibility of importing good quality non-coking coal for power generation was considered. The gross calorific value and the c.i.f. price of imported coal were taken as 6000 kcal per kilogram and US \$40 per tonne, respectively.

3.2. Abatement scenario I

This scenario incorporates a greater penetration of renewable technologies for power generation. Installation of 10 000 MW of wind capacity and of 5000 MW of small hydro plant capacity by the year 2011 was assumed, which may be feasible with the appropriate policy measures.

3.3. Abatement scenario II

For this scenario, a larger exploitation of the hydro potential is considered. As mentioned earlier, India has a hydro potential of 84 000 MW (estimated by the CEA). An upper limit of 50 000 MW on hydro capacity was imposed, as against 34 700 MW in the BAU scenario. This requires an average annual addition of 1600 MW for the period 1992-2011.

3.4. Abatement scenario III

Coal based power generation in India will continue to grow in order to meet the increasing power demand. This scenario includes the introduction of clean coal

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[1] 1 Btu = 1.055×10^3 J.

technologies with the aim of reducing emissions. The integrated gasification coal combustion (IGCC) technology is considered to be technically and economically viable by the year 2011. It is assumed that it will not be feasible to add more than 5000 MW of capacity by the year 2011 with the use of these technologies.

3.5. Abatement scenario IV

In addition to the measures intended for the above mentioned alternative scenarios, this scenario considers for the year 2011 a further reduction in CO_2 emissions by 25% compared with that of the BAU scenario. An additional constraint on the reduction of CO_2 emissions was incorporated in this scenario. All other assumptions are the same as those in the BAU scenario.

4. RESULTS AND ANALYSIS

4.1. Demand

The peak load demand at the bus-bar as estimated by the model is shown in Fig. 1. The growth rate in peak load demand at the national level was estimated at 6.9% and 6.4% for the periods 2001–2006 and 2006–2011, respectively. The lower growth rate in the latter period can be explained by a reduction in system losses due to improvements in the transmission and distribution system.

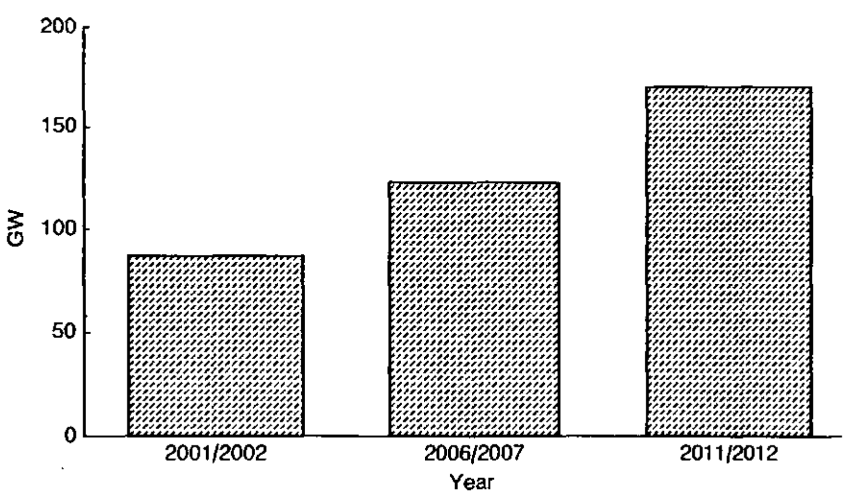

FIG. 1. Peak load at bus-bar.

4.2. Supply

4.2.1. Business-as-usual scenario

For the BAU scenario, the generation requirement was estimated at 590.8 TW·h, 834.6 TW·h and 1179 TW·h for the years 2001/2002, 2006/2007 and 2011/2012, respectively. The power generation capacity requirements were estimated by the model at 123 900 MW, 171 600 MW and 231 700 MW for the years 2001/2002, 2006/2007 and 2011/2012, respectively. This represents a growth rate in capacity addition of 6.2%, 6.7% and 6.2% for the periods 1992–2001, 2001–2006 and 2006–2011, respectively. The higher growth rate for the 10th Five Year Plan (2006–2011) is related to the higher demand that is due to the higher growth rate in the GDP for this period. The growth rate in capacity over the period 1992–2012 was worked out as 6.3% per annum. The capacity peak load ratio for the three years was set at 1.41, 1.40 and 1.38. This implies that it would be necessary to create excess capacities of 41%, 40% and 38% for these years in order to give a 100% guarantee that the peak load demand will be met. The rate of decline in excess capacity requirement is predominantly due to improvements in future plans for meeting the peak load demand.

Figure 2 shows the technologies for the power generation capacity requirements in India in absolute figures, and Fig. 3 gives the technology mix for power generation in percentages. It can be seen that coal, which is the cheapest option for base load operation, continues to dominate the future capacity as well as the technology mix for power generation. The share of coal in power generation increases from 70% in 1992/1993 to 80% in 2011/2012; this is also due to the limited availability of other resources such as gas and hydro. Power generation based on imported coal is cheaper than that based on nuclear power. The generation capacity based on gas is constant in the two years 2006/2007 and 2011/2012, since the gas supply from domestic and imported sources is kept constant for the year 2006/2007 and afterwards.

The average capacity utilization of the power system was calculated as 4768 kW·h/kW, 4863 kW·h/kW and 5089 kW·h/kW for the years 2001/2002, 2006/2007 and 2011/2012, respectively, as compared with 4161 kW·h/kW for 1992/1993. This improvement reflects the assumption of a gradual improvement in the plant load factor.

The fuel demand for secondary power generation is presented in Table I. Over the period 1992–2012, the coal requirement in the Indian power system will grow at a rate of 6.8% per annum. In the years 2006/2007 and 2011/2012, 26×10^6 t and 68.7×10^6 t of coal, respectively, will have to be imported for the power sector. The available imported natural gas, assumed to be 5×10^9 m^3 for 2001/2002 and 10×10^9 m^3 for later periods, will be fully used by the power sector.

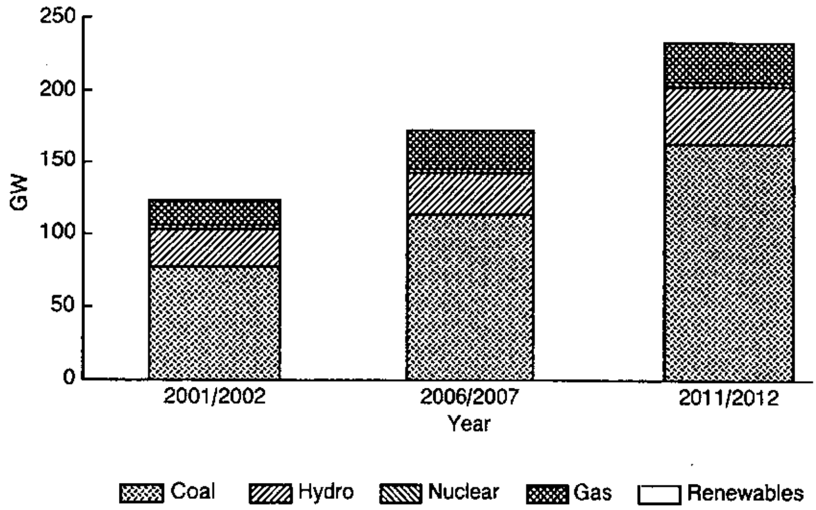

FIG. 2. Technology mix for the power generation capacity requirements in India (absolute figures).

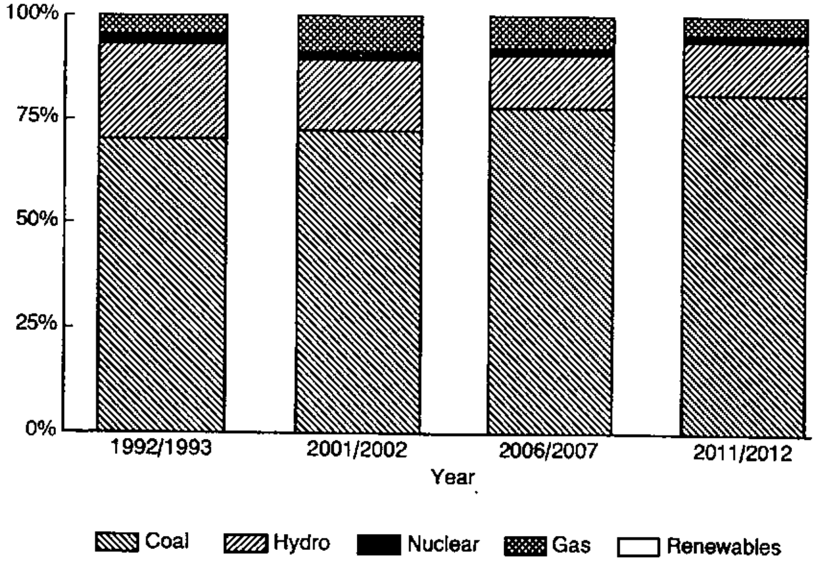

FIG. 3. Technology mix for power generation in India (percentages).

TABLE I. FUEL DEMAND FOR SECONDARY POWER GENERATION

Fuel	1992/1993	2001/2002	2006/2007	2011/2012
Coal (10^6 t)	151.6	260.7	375.6	535.7
Fuel oil (10^6 t)	2.4	3.6	4.9	6.5
Natural gas (10^9 m^3)	5.0	14.0	19.0	19.0

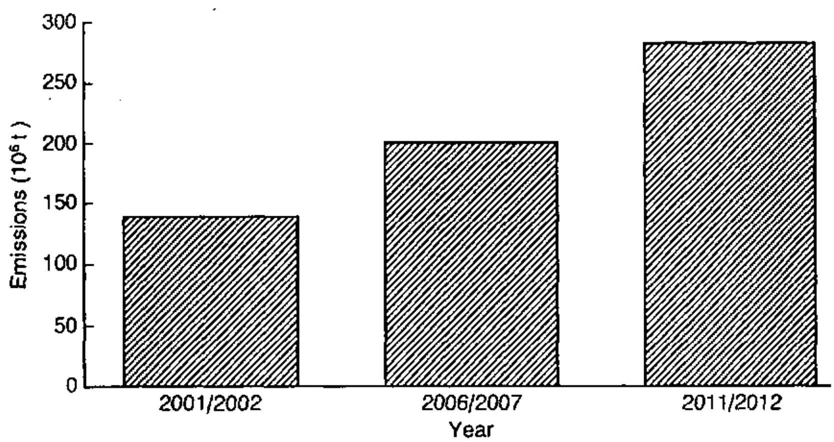

FIG. 4. Carbon dioxide emissions from the power system (BAU scenario).

The net present values of the power system costs as estimated by the model for the years 2001/2002, 2006/2007 and 2011/2012 are 796 × 10^9 rupees, 1304 × 10^9 rupees and 2006 × 10^9 rupees, respectively, at 1993/1994 constant prices.[2] Finally, the CO_2 emissions from the power sector (BAU scenario) are shown in Fig. 4. In this scenario, the CO_2 emissions from the power sector in the year 2011/2012 will increase more than three times compared with the present level of about 80 × 10^6 t CO_2.

[2] 1 US dollar = 31 rupees.

4.2.2. *Abatement scenarios*

As mentioned earlier, these scenarios were developed only for the year 2011. Figure 5 compares the CO_2 emissions and the associated system costs for these scenarios as estimated by the model used for the BAU scenario.

For the abatement scenarios I, II and III, the potential reductions in CO_2 emissions were worked out as 2%, 12% and 1%, respectively, compared with those in the BAU scenario. For scenario IV, which considers all abatement measures and aims at a 25% reduction in CO_2 emissions compared with the BAU scenario, the

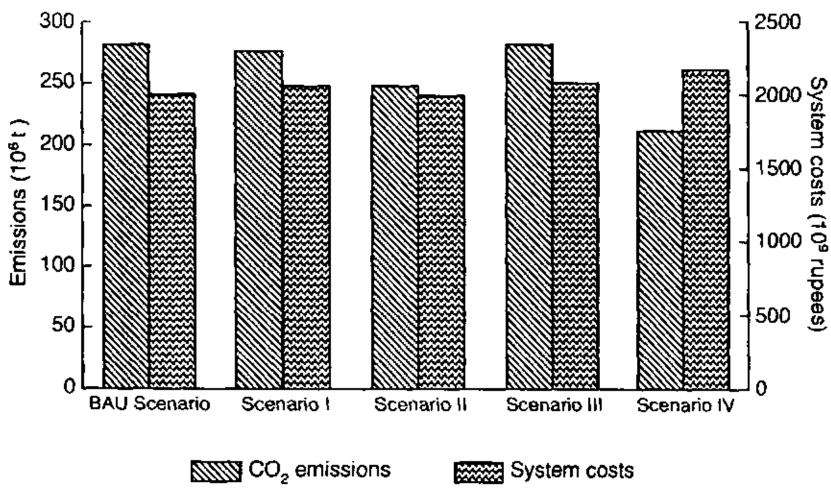

FIG. 5. Carbon dioxide emissions and system costs for different scenarios.

TABLE II. POTENTIAL AND MARGINAL COST OF CO_2 REDUCTION IN THE INDIAN POWER SECTOR

	Scenario I	Scenario II	Scenario III	Scenario IV
CO_2 reduction (10^6 t)	6.0	34	2.6	70
Marginal cost of CO_2 reduction (US $ per t CO_2)	209.6	(−) 18.99	732.0	65.0

model estimated a nuclear capacity of 10 000 MW compared with 2000 MW in the BAU scenario. This implies that the assumed abatement measures are not sufficient to achieve a 25% reduction in emissions. On the other hand, the system cost increases by 1.9%, 2.9% and 7% in abatement scenarios I, III and IV, respectively.

The calculated absolute CO_2 reduction potential and the associated marginal cost per tonne of CO_2 emissions reduced, for the four abatement scenarios compared with the BAU scenario, are presented in Table II.

The negative marginal cost for abatement scenario II has already been explained. The higher marginal cost for abatement scenario I is due to the low capacity utilization factor of renewable technology. In India, the capital cost per megawatt of wind capacity and small hydro capacity is at a par with the cost of conventional technologies used for electricity generation during the period of base load demand. However, the PLF of renewable technologies is 25–30% compared with a minimum PLF of 60% achieved with conventional technologies during the period of base load demand.

The capital cost per megawatt of capacity generated with the clean coal technology is higher by 20 million rupees than that of capacity generated with conventional technology. This explains the high marginal cost of CO_2 reduction in abatement scenario III. Scenario IV indicates that when all abatement measures as described in Scenarios I–III are incorporated and with an additional nuclear capacity of 8000 MW, a reduction of 70×10^6 t C is possible, for which an additional cost of US $65 per t C will be incurred. This cost will decline to US $42 per t C for a reduction of 56×10^6 t C (20% more than that for the BAU scenario).

5. CONCLUSIONS

The Indian power system with a present capacity of 70 000 MW will have to be expanded more than threefold. Therefore, if the present power generation mix continues, the amount of coal burnt by the power sector will be of the order of 535×10^6 t, which will triple the CO_2 emissions from the system. Hence, it is crucial to adopt some measures to limit CO_2 emissions. Three measures are discussed in the present study — enhanced penetration of renewable technology, introduction of cleaner technologies for coal combustion and accelerated development of hydro potential.

Realizing the importance of the use of renewable energies in meeting the vast energy requirements in rural areas as well as the importance of renewables for a clean environment, the Government of India has drawn up a detailed action plan to promote these technologies. Financial and fiscal incentives (such as tax-exemption and loans at low interest rates) are provided to attract private capital in this area. This thrust should continue with proper monitoring (to avoid misuse of these incentives) also for the period of larger penetration of these technologies.

An accelerated development of hydropower will not only decarbonize the power system but also provide cheaper electricity. An appropriate policy is needed to attract private investment. Guidelines are required regarding a financial package for rehabilitating people affected by a project; this will reduce the time required for acquisition of land for new sites. Also, better co-operation between the Indian Government and the Governments of other States is required to resolve disputes on sharing of water resources.

Since coal will continue to be the mainstay in the Indian energy scenario, it is imperative to adopt clean coal technologies that will provide a higher heat rate and hence low coal consumption per unit of power generation. Although the IGCC technology is commercially available abroad, it is still not suitable for use in India because the Indian coal has a high ash content. Greater R&D efforts are required on this front. Moreover, even if coal of suitable quality is imported, power producers may not opt for this technology because of its high cost (the capital cost of 1 MW of capacity based on the IGCC technology is around 55 million rupees as against 35 million rupees for 1 MW of capacity based on conventional technology). Large R&D efforts are required to bring the cost at a par with the cost of conventional coal combustion technology.

Finally, although the nuclear option may be more expensive, even compared with power generation using imported fuel, it may be necessary to add some nuclear based power generation capacity, with proven safety measures included, to the Indian power generation system in order to sustain a clean atmosphere.

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ECONOMIC, ENERGY AND ENVIRONMENTAL ASSESSMENTS OF THE FRENCH NUCLEAR PROGRAMME

M. VIELLE
Service des études économiques,
Direction de la stratégie et de l'évaluation,
Commissariat à l'énergie atomique,
Paris, France

Abstract

ECONOMIC, ENERGY AND ENVIRONMENTAL ASSESSMENTS OF THE FRENCH NUCLEAR PROGRAMME.

As environmental issues (particularly questions associated with the greenhouse effect) become a matter of increasing current concern, the French nuclear power programme can, in retrospect, be seen to have had a very positive impact on emissions of atmospheric pollutants. The paper presents two studies performed with two models of different specifications. The first study, using a standard macroeconomic model (Micro-Mélodie), is based on a scenario assuming that France, at the beginning of the 1970s, had not decided to invest in a massive PWR programme but instead limited itself to fossil fuels. The second study, using a general equilibrium model (Gemini-E3), assesses the impact of a nuclear moratorium adopted in 1985. In each of these two studies, the macroeconomic and environmental impacts are stressed. From both studies it has become clear that the French nuclear programme has improved the efficiency of the French economy, enhanced the independence in total energy supply and, last but not least, led to a considerable reduction of atmospheric pollutant emissions. These two assessments are discussed in detail.

1. THE FRENCH NUCLEAR PROGRAMME: AN EXCEPTIONAL CONTRIBUTION TO THE SUPPLY OF ELECTRICITY

In France, nuclear power generation contributes decisively to energy supply. In 1994, nuclear power production was 341.8 TW·h, i.e. more than 75% of the total electricity generation, with a total installed capacity of about 58.5 GW. In France, nuclear power is by far the most competitive source of base load electricity generation (see Table I). In 1994, the nuclear sector (including research, plant construction, the nuclear fuel cycle and electricity generation) represented F.Fr. 104×10^9, i.e. 1.5% of the French gross domestic product [1]. Moreover, the French nuclear industry exports electricity. In 1993, 61.7 TW·h from nuclear production were exported, which contributed F.Fr. 14.2×10^9 to the credit side of the balance of

TABLE I. ELECTRICITY GENERATION COST IN FRANCE (F.c. 1993/kW·h)

Option	Investment	Operation	Fuel	R&D	Total
Nuclear	13.6	5.6	4.5–6.2	0.4	24.1–25.8
Coal[a]	11.3	5.8	11.7–17.7	—	28.8–34.8
Gas[b]	5.9	2.4	21.1–27.4	—	29.4–35.7

Discount rate 8%, operating time 6000 hours/year, commercial commissioning in the year 2003.
[a] Circulating fluidized bed combustion.
[b] Combined cycle plant.
Source: Ministère de l'industrie.

payments. For the same year, the exports of Framatome are assessed at about F.Fr. 2 × 10^9, corresponding to the manufacture and erection of heavy components and maintenance services. Cogéma, the French nuclear fuel operator, sold nuclear materials and services for F.Fr. 9.3 × 10^9. So, nuclear activities contributed more than F.Fr. 25 × 10^9 to the balance of payments. It is also evident that nuclear power has contributed to reducing emissions of atmospheric pollutants in France.

This paper presents two studies [2, 3], which try to assess the economic, energy and environmental impact of the French nuclear programme. First, the two models used are described briefly and then each study is discussed separately. The main results are summarized in the conclusion.

2. MICRO-MELODIE AND GEMINI-E3: TWO MACROECONOMIC MODELS

Micro-Mélodie [4] and Gemini-E3 [3] are two macroeconomic models that were developed by the Commissariat à l'énergie atomique. Each of the models incorporates a detailed representation of the energy sectors/products, with a classification adapted to the energy sectors and a specific representation of them. In the two models electricity is described separately on the basis of a technological representation where the load curve is a major component (see below). The links between the energy sectors/products and the macroeconomic part have been established with great care. Concerning the macroeconomic framework, the two models are based on different specifications. Micro-Mélodie is mainly based on neokeynesian specification, with simultaneous neoclassical demand and supply. Gemini-E3 is a general equilibrium model based on Walrasian theory and works mainly as a comprehensive tool devoted to performing cost-benefit analysis of various policy scenarios. Another major difference is the geographic area: Micro-Mélodie gives only a description of the French economy; Gemini-E3 is a worldwide model in which three areas are taken into account: France, other members of the European Union and the rest of the world.

Micro-Mélodie

Zone: France
Sectors/commodities: three (electricity, fossil fuel, others)
Running period: 1970–2015
Economic background: neokeynesian theory and neoclassical theory
Production function: Translog
Technological for electricity
Households' demand: Translog
Atmospheric pollutant emissions: CO_2, SO_2 and NO_x

Gemini-E3

Zones: France, other European countries, rest of the world
Sectors/commodities: 11, of which four are for energy
(coal, gas, electricity, oil and refined products)
Running period: 1985–2000
Economic background: Walrasian theory
Production function: Nested CES
Technological for electricity and crude oil
Households' demand: Linear expenditure system
Atmospheric pollutant emission: CO_2

3. TWO DIFFERENT ASSESSMENTS OF THE FRENCH NUCLEAR PROGRAMME

3.1. France without nuclear power

In this scenario we assumed that France did not invest in a massive PWR programme. If a programme for the replacement of nuclear power plants by fossil fuel fired power stations had been initiated in 1970, the first unit would have been brought into service in 1977. The date of commissioning would have been in the period immediately after the increase in crude oil prices and thus the fuel used would have been coal.

3.1.1. Brief description of the coal scenario

In order to secure a relatively high level of independence in energy supply, the French authorities would have had to develop coal mining. Taking into account the technical characteristics of coal deposits in France, an increase in the output of coal of 5 Mt per annum in the Lorraine region was envisaged, while the remaining coal needed for electricity generation would have been imported from those countries which generally supply coal to France. Initially, all of the coal fired units would have been constructed with grate furnaces. We assumed that all coal fired units, with the exception of the four units constructed in the Lorraine region, would have been fitted with effective desulphurization equipment, in the form of flue-gas scrubbers, operating at 90% efficiency. Fluidized bed technology would have been introduced progressively between the years 2000 and 2005. The actual cost of investment recorded for a coal fired power plant (see Table I) was adjusted in order to take into account the various impacts arising from the development of a major programme for the production of electricity from coal. Large scale plant construction would have reduced the cost by 7% before 1975 and by 9% after 1975. The consequence of an increased number of units per site was assessed at 3% cost reduction. A higher capacity per unit would have entailed a cost reduction of 4% after 1975. In contrast, difficulties in connection with siting would have increased the cost by 3% before 1975 and by 5% after 1975, and installation of desulphurization equipment would have led to a 20% higher cost after 1975.

On the other hand, the nuclear option is characterized by high levels of industrial investment in the nuclear fuel cycle. A proportion of these investments (approximately F.Fr. 33 $\times$ 10^9 at 1994 values, mainly for the construction of UP2 and for prospecting) had already been committed prior to 1970 and may be classified as investments in the operation of graphite gas units. However, the major part of the investment in the nuclear fuel cycle took place after 1970. In our coal scenario, this expenditure (calculated at F.Fr. 110 $\times$ 10^9) would not have been required. For nuclear power plants, the total cost of investment from 1970 to the present time was estimated at F.Fr. 420 $\times$ 10^9 on a plant-by-plant basis. For the period from 1970 to 1994, the total cost of the nuclear programme was estimated at F.Fr. 530 $\times$ 10^9. The coal option, like the nuclear option, must be considered initially in terms of investment in the fuel cycle, i.e. including the cost of increased coal production in the Lorraine region and the extension of harbour capacity. The new harbour infrastructure and the new coal mines require an investment of F.Fr. 50 $\times$ 10^9. To provide the same net capacity, 62 GW(e) of coal fired capacity would have been required for replacing 64 GW(e) of nuclear capacity (since approximately 2 GW(e) are required to supply the Eurodif plant). This investment would have totalled F.Fr. 335 $\times$ 10^9 at 1994 values. For the same net capacity, the total cost of the programme for the production of electricity from coal would have been F.Fr. 385 $\times$ 10^9. We assumed a 10% increase in the international coal price for the period from 1980 to 1986. Increased demand of coal in France at a time when the international market was restricted would undoubtedly have led to an increase in energy prices. In response to the increased coal demand in France, the worldwide demand on the international steam coal market would have increased by 20%. For the period after 1995, our assumptions of coal prices are based upon US $44 per tonne of coal by the year 2010.

3.1.2. Effects on the energy sector

Figure 1 shows the actual past development of the structure of electricity production in France. Figure 2 shows how this structure would have developed in France without nuclear power. In terms of electricity supply, the situation in a nuclear free France would have been comparable with the situation in the United Kingdom, with 70% of electricity produced from fossil fuel plants and approximately 30% produced from nuclear and hydroelectric plants. At present, the price per kilowatt-hour of electricity under the coal scenario would be some 15% higher. The increase in electricity prices would have reached 20% in 1986 (before the decrease in the international price of coal). By now, the price of electricity would be highly sensitive to fluctuations in the price of coal. Consequently, by the year 2000, the price of electricity would increase by 16%. In a nuclear free France, the increase

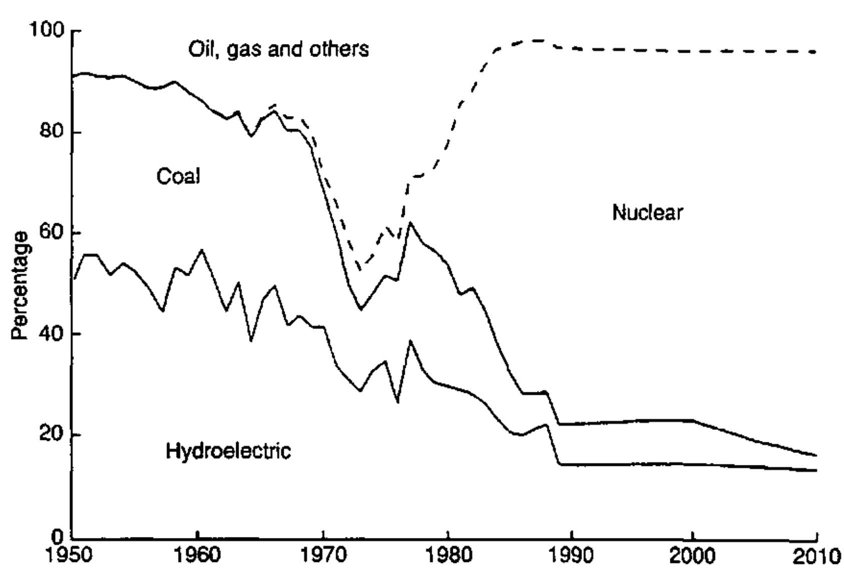

FIG. 1. Structure of electricity production in France with nuclear power. Source: EDF Handbook and GPE scenario C.

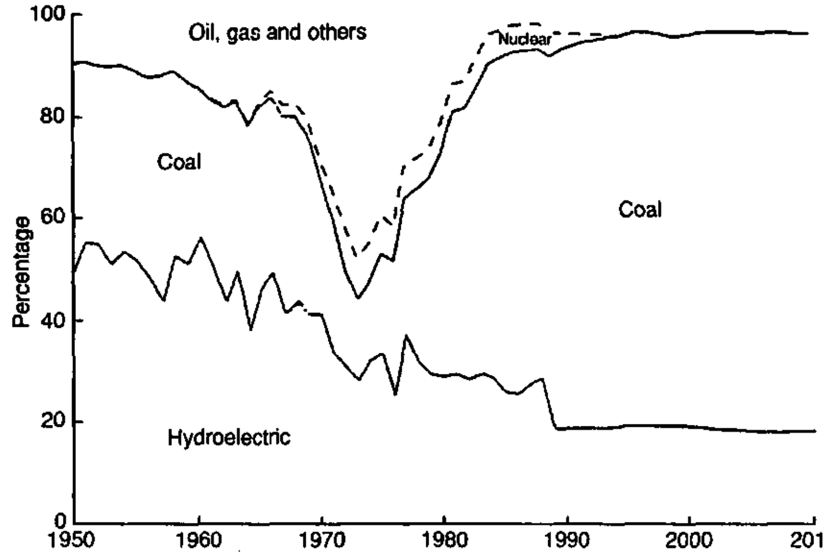

FIG. 2. Structure of electricity production in France without nuclear power. Source: Micro-Mélodie.

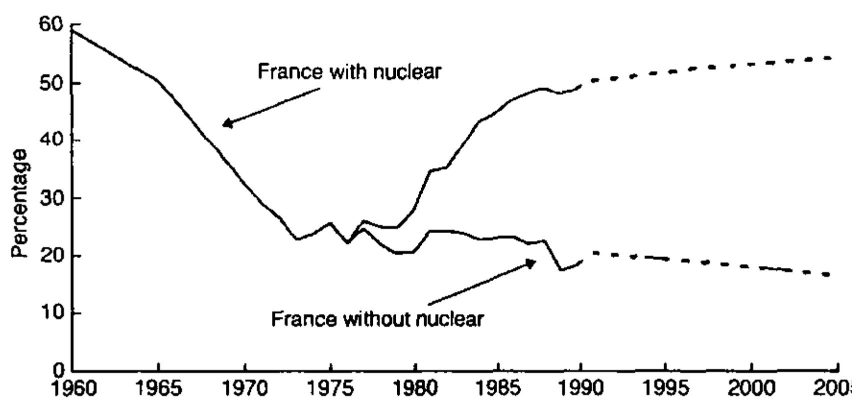

FIG. 3. Independence in energy supplies. Source: Key Energy Statistics, 1981; and GPE scenario C.

in electricity prices would lead to a decline in electricity consumption and to the replacement of electricity by other forms of energy. In the energy sector, this decline in consumption would be due mainly to the absence of the Eurodif plant, which accounts for an annual electricity consumption of 20 TW·h. In the industry, the impact of higher electricity prices would vary according to the industrial sector concerned. The impact on other sectors would be extremely limited. In the residential sector, heating would also be most affected by the electricity prices. In particular, high electricity prices would lead to much less growth in central electric heating, with an estimated decline in electricity consumption of 10 TW·h. The net exports of electricity would be close to the level of supplies delivered under contracts based upon long term cost differentials. In a nuclear free France, the comparative advantage of the French electricity costs would be considerably reduced, which would lead to total discontinuation of electricity exports (63.4 TW·h in 1994). In 1994, the total drop in national electricity production would have been close to 115 TW·h, while the final energy consumption would have decreased by 28 TW·h. The overall structure of the final energy consumption in a nuclear free France would have been close to the present pattern. The same can certainly not be said of the primary energy balance. The fossil fuel consumption in France would have been almost 60 Mtoe higher than the current value, with coal for electricity production accounting for the major proportion of this figure. Independence in energy supplies, as shown in Fig. 3, would currently be approximately 20% (as against its actual level of nearly 50%), which is close to the figure for 1973.

3.1.3. Macroeconomic effects

The structure of the economy (see Table II) would have been modified by the following three factors: decreasing investment in the electricity sector and the fuel cycle, rising electricity prices, and a substantial reduction of the independence in energy supplies. Chronologically, the first of these factors having any impact would be the decreasing investment in the electricity sector resulting from the discrepancy in the cost of investment per kW(e) between installed nuclear capacity and coal fired capacity and resulting from the reduction of the total net capacity required (which, in itself, would result from the reduced demand for electricity). The macroeconomic

TABLE II. NUCLEAR FREE FRANCE — MACROECONOMIC IMPACT

Year	1975	1980	1985	1990	1995	2000	2005	2010
GDP	0.0	−0.4	−1.6	−1.3	−1.3	−1.3	−1.6	−1.6
Imports	−0.1	0.1	0.3	0.1	−0.1	−0.1	−0.3	−0.3
Exports	0.0	0.2	−0.2	−0.4	−0.4	−0.2	−0.2	−0.2
Consumption	0.1	0.1	−0.9	−0.9	−1.1	−1.2	−1.4	−1.6
Investment	−0.5	−1.9	−2.4	−1.3	−0.7	−0.5	−1.7	−1.3
Price of consumption	−0.4	−0.4	0.9	0.4	0.7	0.7	0.8	1.0

Source: Micro-Mélodie; percentage deviation from the reference scenario.

impact of this factor would be equivalent to a keynesian multiplier. In general terms, there would have been two main consequences, namely a significant reduction of economic activities (see Table II) and a reduction of the pressure on the trade balance towards the mid-1970s. The remaining two factors would have had a significant effect from the early 1980s onwards, with their impact exacerbated by the fact that this was a period of high prices on international coal markets. Higher electricity prices would have increased the production costs of companies, which would then have passed on these increased costs to the consumer in the form of higher prices. Households would have been affected by the increase in the cost of domestic electricity itself, and by the increased price of goods and services involving electricity. In wage negotiations, these increases would have been offset only to a limited extent by increased earnings, since index linking would have been limited by a significant rise in unemployment. By the present day, there would have been a 0.8% reduction in purchasing power. By the year 2000, this reduction would reach 1.2%. The main effect of this loss of purchasing power would have been a decline in household consumption (1.1% in 1995), which would have had a negative impact on economic activities (−1.3% in 1995). Nearly 100 000 jobs would have been lost. Reduced independence in energy supplies has a negative impact on the trade balance. This annual negative impact would have been almost half of the deficit actually recorded for the cif/fob trade balance. The decrease in final energy demand (investment and consumption) would have had a positive impact on the external trade balance (by reducing imports and releasing capacity for exports), but this would not, in itself, have been sufficient to offset the major increases in national energy costs. The cumulative deficit over the period from 1981 to 1990 would have exceeded F.Fr. 110×10^9 at 1994 values. Over the decade from 1991 to 2000, this cumulative deficit would reach F.Fr. 210×10^9. At present, the impact of the French nuclear programme (in terms of economic activities, employment and external trade) is generally positive. If this programme had not been implemented, the impact might be compared with that of an oil crisis, with a long term increase in the price of oil by US $20 per barrel.

3.1.4. Environmental impacts

We now consider the consequences of the French nuclear programme in terms of emissions of atmospheric pollutants. In the coal scenario considered, these gases are generally emitted by the generating plant. However, the significant economic changes brought about by the use of coal for electricity production would certainly have had some impact on these emissions, particularly through the substitution of energy sources by other sources for the overall energy demand. All emissions of atmospheric pollutants (including indirect or induced emissions) have been recorded. However, we have taken no account of changes in the primary energy balance of foreign countries, such as Germany or Italy. The current amount of sulphur dioxide

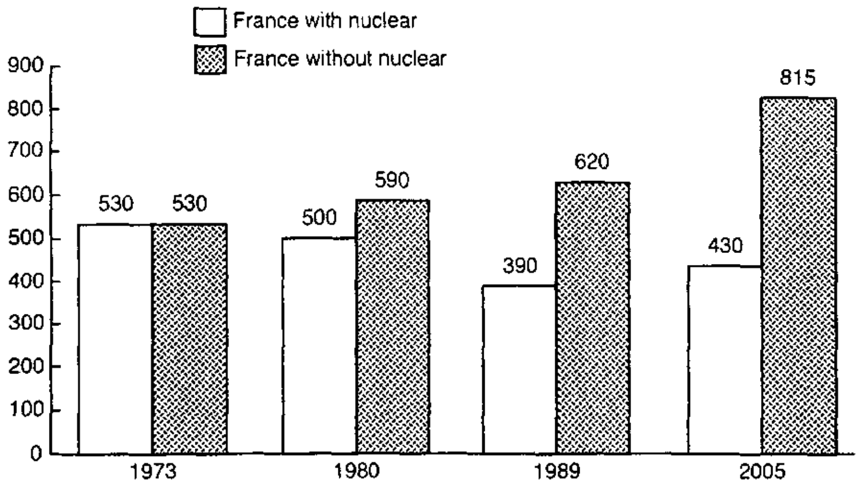

FIG. 4. Carbon dioxide emissions in France (Mt of CO_2).

emissions would be higher by 230 kt per annum — an increase of 18%. This increase (which, after all, may be regarded as relatively modest) is closely linked to the assumption that effective desulphurization measures would have been applied to all coal fired power plant units constructed (otherwise, the sulphur dioxide emissions would have reached 11 400 kt per annum). In a nuclear free France, the sulphur dioxide emissions would reach 250 kt per annum by the year 2000. At present, the amount of nitrogen oxide emissions would be higher by 510 kt per annum — an increase of 29%. In a nuclear free France, these extra nitrogen oxide emissions would reach 720 kt per annum by the year 2000. The amount of carbon dioxide emissions (390 Mt per annum in 1989) would be exceeded by 230 Mt per annum. By the year 2000, these extra emissions would reach 340 Mt per annum (see Fig. 4), which amounts to 6 Gt of carbon dioxide emissions over the next twenty years, calculated on a cumulative basis.

3.2. Nuclear moratorium

In this study, we assume that in 1985 France adopted a nuclear moratorium leading to the cancellation of all investments in nuclear plants, starting from the year 1985.

3.2.1. Effects on the energy sector

We assume that the net exchanges of electricity are gradually reduced and that they will exactly balance by the year 2000. All remaining nuclear power plants

(37.4 GW) will then be dedicated to French consumption. The use of the model Gemini-E3 yields the following results. The national demand for electricity will be reduced by about 8% in the medium to long term, with a price increase of about 7% (for households). Concerning production, the cancelled nuclear plants are replaced by coal and gas plants. By the year 2000, the installed capacities will be reduced by 17 GW. The investment shares are 12 GW for coal units and 12 GW for gas units. By the year 2000, the structure of thermal electricity generation will be 75% for nuclear, 18% for coal and 7% for gas, compared with the reference case (91% for nuclear, 5% for coal and 4% for gas).

3.2.2. *Macroeconomic effects*

The results (see Table III) are mainly explained by three factors: the increase in the electricity price, the devaluation of the French Franc and the decrease in the

TABLE III. NUCLEAR MORATORIUM — MACROECONOMIC IMPACT

Variables	1985	1990	1995	2000
France				
GDP	0.00	0.01	0.10	0.10
Import	0.00	−0.10	−0.27	−0.31
Export	0.00	0.82	1.41	1.82
Consumption	0.00	−0.31	−0.44	−0.63
Investment	0.00	−0.01	−0.06	−0.15
Europe				
GDP	0.00	0.04	0.10	0.15
Import	0.00	0.42	0.46	0.37
Export	0.00	−1.04	−1.34	−1.27
Consumption	0.00	0.28	0.45	0.45
Investment	0.00	0.59	0.73	0.89
Rest of the world				
GDP	0.00	−0.01	−0.04	−0.05
Import	0.00	−0.64	−0.73	−0.61
Export	0.00	0.48	0.49	0.34
Consumption	0.00	−0.05	−0.08	−0.08
Investment	0.00	−0.13	−0.18	−0.20

Source: Gemini-E3; percentage deviation from the reference scenario.

interest rate. The increase in the electricity price will induce a substitution of some energy sources by others (coal, gas, oil and raffinate products) and a change in other factors of production. Furthermore, households will reduce their electricity consumption, with a resulting decrease in electricity generation by 20%. The second factor is related to the increase in imported resources for electricity generation (gas and coal) which induces an ex-ante deficit of the trade balance. This deficit will be obliterated by a devaluation of the French Franc (3.9% against the ECU and 2% against the US dollar by the year 2000). The export of French products (except electricity) will be promoted by the devaluation, and total exports will increase by 1.8%, while at the same time the imports will decrease by 0.3% by the year 2000, even if the energy imports increase. The third factor is related to the decrease of investments in the electric sector and the fact that gas and coal are less capital intensive. Thus the decrease of the capital demand by the electric sector will lead to a reduction of the interest rate by 2%, which will reduce the cost of capital for other sectors. On the whole, the reduced efficiency of the economy will generate a loss in the welfare of people, whose consumption will be reduced by 0.6% in the year 2000. The GDP will be unchanged because of the devaluation of the French Franc, which will lead to an increase in exports and a decrease in imports. Other European countries will be affected mainly by the revaluation of the ECU against the French Franc, which will lead to similar but opposite macroeconomic effects, but with a smaller magnitude.

3.2.3. Environmental impacts

As for the coal scenario, the environmental effects of this scenario can be determined. This is being done for the whole world, but only concerning carbon dioxide emissions. The current worldwide carbon dioxide emissions would be exceeded by 51 Mt in the year 1990 and by 102 Mt in the year 2000. In France, the carbon dioxide emissions would increase by 37 Mt in 1990 and by 84 Mt in 2000. In Europe, the increase would be equal to 29 Mt in 1990 and to 47 Mt in 2000.

4. CONCLUSIONS

As environmental matters have become the focus of increasing concern, the implementation of a major nuclear power programme has allowed France to enjoy the benefits of a comfortable position. In France, the emissions of carbon dioxide per capita are among the lowest in the industrialized world.

In terms of economic impact, the most obvious consequence of this programme is the stability of the electricity prices resulting from the increasing self-sufficiency of France in energy supplies (from 22% in 1973 to 50% in 1993). The two studies, which use two different models, show that the nuclear industry has a positive impact in terms of the welfare of people, measured by the consumption of household goods. Thus we can say that the French nuclear industry has improved the French economic efficiency, has increased the common welfare and has significantly contributed to the abatement of atmospheric pollution.

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IMPACT OF INCORPORATING ENVIRONMENTAL EXTERNALITIES ON ELECTRIC RESOURCE PLANNING
Selected case studies

J. GEIDL, S. KANHOUWA
Office of Coal, Nuclear, Electric and Alternate Fuels,
Energy Information Administration,
United States Department of Energy,
Washington, DC, United States of America

Abstract

IMPACT OF INCORPORATING ENVIRONMENTAL EXTERNALITIES ON ELECTRIC RESOURCE PLANNING: SELECTED CASE STUDIES.

Electricity constitutes a critical input in sustaining economic growth and development and the well-being of inhabitants in the United States of America. However, there are by-products of electricity production that have an undesirable impact on the environment. Most of these are emissions introduced by the combustion of fossil fuels. In a generic sense, the adverse environmental impacts caused by these emissions are called 'externalities'. Federal and State regulatory authorities in the USA have been engaged in making sustained efforts to reduce or limit the environmental consequences of power generation. The Federal approach tends to be more in the form of 'command and control'. As a result, compliance with Federal requirements leads to added costs for the utilities and increases the costs of power sold by them. Federal actions may, therefore, be seen as a way of incorporating and internalizing externalities. Treatment of externalities at the State level is far from uniform. The paper describes the regulatory policies adopted by three States that monetize externalities — Massachusetts, Wisconsin and California. The treatment of environmental externalities in electricity generation and in planning for resources is analysed. Thus, the paper provides an evaluation of the impact of incorporating environmental externalities on electric resource planning. It is concluded that the requirement of the States to incorporate externalities in the resource planning process had little impact on the planned resource mix in each of the three States. Lack of capacity through the end of the decade and falling natural gas prices contribute to this outcome. Structural changes that currently confront the electric utilities in the USA render the future of externality considerations rather uncertain at the State level.

1. INTRODUCTION

The study entitled "The Impact of Incorporating Environmental Externalities on Electric Resource Planning: Selected Case Studies" was undertaken by the Energy Information Administration (EIA) of the US Department of Energy (DOE).

The study was initiated to meet the requirements of EIA's analytical agenda, as well as to meet the specific guidelines of the International Atomic Energy Agency (IAEA) with respect to the co-ordinated research project initiated under the aegis of the ongoing DECADES project.

The legislation that created the EIA in 1977 vested it with an element of statutory independence to ensure that its main activities are not influenced by politics or bias. These activities include objective data collection, assembly, evaluation, analysis and dissemination. Associated with these activities is the need to perform credible analyses in support of deliberations by decision makers. Thus, this report does not purport to represent the policy positions of the DOE or the US administration.

This analysis report examines policies adopted by selected State regulatory authorities regarding the treatment of environmental externalities within the framework of the utility regulatory process and evaluates their impact on the resource selection process. The three States (Massachusetts, Wisconsin and California) selected in this study are among those that have been actively involved in the consideration and monetization of externalities within the regulatory process. The analysis is based on a review of documents that are in the public domain and available from State public utility commissions and electric utilities. Also, meetings were held with officials at public utility commissions and with officials at the largest investor owned utility in each of the three States.[1] In addition, the report examines the possible future of externality considerations in the light of structural changes that are likely to occur in the electric utility industry. These changes stem from the Energy Policy Act of 1992, which aims at promoting competition in the electric utility industry by initiating various actions designed to achieve this objective.

2. WHAT ARE EXTERNALITIES?

Economists find it easy to provide a conceptualization of the term 'externality' while continuing to struggle over formulating its precise definition. Broadly speaking, the generic term 'externality' includes costs or damages and benefits resulting as unintended by-products of an economic activity and accruing to someone other than the parties involved in the activity.

Two examples illustrate the externality concept. Assume the simultaneous existence of apple growing and bee keeping activities located in close proximity to each other. An expansion in the activities of the apple growing farmers to increase apple production provides an unexpected increase in apple blossoms. This development, in turn, leads to an increase in the honey production as well. Within the framework of the market pricing mechanism, the bee keeper does not compensate the apple

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[1] Meetings were conducted by S. Kanhouwa of EIA and R. Lee of Oak Ridge National Laboratory in November 1994.

farmer for the largess.[2] Consider now the case of a poor widow supporting herself by doing hand laundry, which is hung outside to dry. However, her wash blackens because of a smoke emitting factory next door. Here again, the widow receives no compensation for this damage to her laundry.[3]

The examples cited above are what the economists call external economies or external diseconomies.[4] These terms have since been abbreviated into what are commonly called 'externalities' or the alternative term 'spillover effects'.

3. EXTERNALITIES AND ELECTRIC POWER GENERATION

Using the above concept of externalities as the starting point, economists point out that costs and/or benefits of externalities do not enter in the market pricing calculations of the parties concerned where the primary focus is to recover the sum of privately incurred costs. Including the costs or damages caused by externalities (i.e. the impacts) in the market pricing structure would permit recovery of what are called 'social costs'. In such a case, those who suffer damages would receive compensation and those who receive benefits would pay according to the social costing doctrine.

3.1. Environmental externalities and pricing electric power[5]

The discussion in the preceding paragraphs makes it possible to take into account environmental externalities in the context of electric power generation. Power generation involves a process in which the actions of economic agents (i.e. those producing electric power) are not appropriately reflected in the market prices charged for their product. True resource costs should include both the private costs incurred to provide power and the external costs of damage (or deterioration in quality) to the environment caused by power generation. Where true resource costs are not fully recovered, the price charged for electric power is lower than it would

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[2] This example has been adopted from the writings of Meade (MEADE, J.E., "External economies and diseconomies in a competitive situation", A.E.A. Readings in Economic Welfare, R.D. Irwin Inc., Homewood, IL (1969) 185–198).

[3] This example appears in FERGUSON, C.E., Microeconomic Theory, R.D. Irwin Inc., Homewood, IL (1972) 496–497.

[4] Alfred Marshall was the first economist to dwell on the subject of external economies and external diseconomies. For further details, see MARSHALL, A., Principles of Economics (1890).

[5] This section focuses on externalities and electric power generation to the exclusion of other segments of the energy sectors. For a further discussion, see FISHER, A.C., ROTHKOPF, M.H., Market failure and energy policy — A rationale for selective conservation, Energy Policy (1989) 397–406.

be if the costs of externalities were to be internalized.[6] Consumption of electric power is thus encouraged, leading to a misallocation of resources (in terms of their most efficient uses) together with an associated impact on social welfare.[7]

3.2. Power generation activities in the United States of America

It is well known that combustion of fossil fuels in the process of generating electricity produces by-products that have an adverse impact on the environment. The magnitude of emissions attributable to power generation activities in the USA is a function of the demand for power and the resources used in generating electricity. Some basic industry statistics are provided below.

Net electricity generation aggregated 2883×10^9 kW·h during 1993. This record power output was met from various fuel sources. Coal provided about 57% of the total net generation, followed by nuclear power at about 21%. Hydroelectric power and natural gas each supplied around 9% of the total. Petroleum products contributed to over 3% of the output, with miscellaneous sources accounting for the balance.[8] During the same year, the industry consumed large volumes of fossil

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[6] The term 'internalization', although used commonly, remains undefined. One definition of 'internalizing an externality' implies the creation of "social conditions where damages (or benefits) from production and consumption are taken into account by those who produce these effects. These social conditions can be created by government regulation, a tort system, bargaining between private parties, or other policy and institutional arrangements. Benefits and damages can exist even when all externalities have been internalized". Another definition states that "internalization of externalities does not mean there are no environmental costs borne outside the utility and their ratepayers. Instead, the utilities and their customers must pay for the environmental resources they consume, just as they pay for concrete, labor, and other inputs to the production of electricity". Both these definitions are extensive in their coverage. *See* Oak Ridge National Laboratory and Resources for the Future, US-EC Fuel Cycle Study: Background Document to the Approach and Issues, ORNL, TN (Nov. 1992) p. xii, and National Association of Regulatory Utility Commissioners, Environmental Externalities and Electric Regulation, Washington, DC (Sep. 1993) 25.

[7] Note that this statement is supported by demonstrated principles of welfare economics. In this context, welfare economics may be viewed as a study of the social desirability of alternative arrangements of economic activities and allocation of resources — that are scarce and have alternative uses — towards a determination of efficient states in which no individual can be made better off without making some other individual worse off.

[8] The net electricity generation increased to 2909×10^9 kW·h in 1994. Data for 1993 have, however, been used, because emission data for the year 1994 are not yet available. Note that electricity generation by non-utility power producers has not been included in the above data.

fuels: over 800 million tons of coal[9], nearly 2700 × 10^9 ft^3 of natural gas and 170 million barrels of petroleum products to generate slightly over two thirds of the domestic output of electricity.[10]

To sustain its operating capability at the levels indicated above, the industry owned nearly 700 GW of generating capability in 1993 together with associated transmission and distribution facilities.[11] Significant levels of investment are required to own and operate these facilities, making the electric utility industry the single most capital intensive industry in the country. Its assets in 1993 were approximately three fourths of one trillion US dollars with aggregate operating revenues at about US \$200 × 10^9.[12] Taken together, these impressive statistics accord the electric utility industry an important place within the US economy.

However, the growth of the electric power sector has not been an unmixed blessing. While electricity has proven itself to be the sine qua non of industrialization and societal well-being, by-products of its production and distribution have an undesirable effect on the environment. Most of these by-products are introduced by the combustion of fossil carbonaceous fuels used in converting thermal energy into electric energy.[13] Pollutants emitted into the air include nitrogen oxides (NO and NO_x), sulphur dioxide (SO_2), traces of heavy metal contaminants, organic pyrolysis

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[9] Tons are short tons throughout the paper: 1 short ton = 2000 lb = 907.18 kg = 0.90718 tonnes.

[10] Energy Information Administration, Annual Energy Review, 1993, DOE/EIA-0384(93), Washington, DC (July 1994) 237.

[11] Nearly 55 GW of generating capacity owned by non-utility generators is excluded. In addition, there were approximately 192 000 miles of transmission lines in 1993, with more than 13 000 miles planned for addition during the next ten years. *See* North American Reliability Council, Reliability Assessment 1994–2003, Princeton, NJ (Sep. 1994) 12.

[12] Energy Information Administration, Financial Statistics of Major U.S. Investor-Owned Electric Utilities, 1993 (DOE-EIA-0437(93)/1, and Financial Statistics of Major U.S. Publicly Owned Electric Utilities, 1993, DOE-EIA-0437(93)/2, Washington, DC (Jan. 1995 and Feb. 1995).

[13] The undesirable environmental effects are significantly larger when the impacts are considered with respect to the entirety of the fuel cycle of any specific fossil fuel. Power generation using conventional methods relies on extracting and transporting a fuel, to its conversion into electric power and finally to the disposition of residual products including generation facilities. Recent studies take into account the totality of effects of each fuel cycle. As an example, methane (CH_4) emitted from coal mining is considered to be a greenhouse gas contributing to global warming. *See* Oak Ridge National Laboratory and Resources for the Future, US–EC Fuel Cycle Study: Background Document to the Approach and Issues, ORNL, TN (Nov. 1992).

TABLE I. GENERATION AND ESTIMATED EMISSIONS FROM US ELECTRIC UTILITY FOSSIL FUELLED STEAM ELECTRIC GENERATING UNITS, 1993

Fuel	Net generation		SO_2 emissions		NO_x emissions		CO_2 emissions	
	10^9 kW·h	Per cent of total[a]	1000 tons	Per cent of total[a]	1000 tons	Per cent of total[a]	1000 tons	Per cent of total[a]
Coal	1639	83.1	13 844	95.9	5288	90.4	1 711 673	87.9
Petroleum	96	4.9	583	4.0	136	2.3	84 129	4.3
Gas	237	12.0	1	<0.5	424	7.2	146 584	7.5
Total	1972	100.0	14 428	100.0	5848	100.0	1 942 386	100.0

[a] Total refers to the total quantity for fossil fired steam electric units only.

Notes: Data in this table are with specific reference to fossil fuelled steam electric generating plants in the USA. The designation steam electric excludes gas turbines, combustion turbines and internal combustion engines. Estimates of emissions are for steam electric plants of 10 MW and more, and are based on fuel consumption using average emission factors as reported in the Environmental Protection Agency's AP-42 Release IV.
Source: Energy Information Administration, Electric Power Annual 1993, DOE-EIA/0348(93), Washington, DC (Dec. 1994), 25, 26, 34, 36, 37, 76.

compounds, and others. Fossil fuels also produce carbon dioxide (CO_2), which absorbs radiant energy and contributes to the global warming phenomenon.[14]

As indicated earlier, fossil fuels currently provide nearly 70% of net electricity generation in the USA. They contribute to emissions of various gases at significantly high levels into the atmosphere. Estimated emissions during 1993 from fossil fuelled steam electric generating units were: SO_2 — 14.4 million tons, NO_x — 5.9 million tons, and CO_2 — 1.94×10^9 tons (Table I).[15] Other major air emissions are volatile organic compounds, carbon monoxide, lead and PM_{10} particulates.[16]

3.3. Federal and State environmental regulations affecting power generation in the USA

There is a growing recognition that emissions attributable to power generation activities have an adverse impact on the environment — locally, nationally and globally. As a result, the concern with respect to the adverse impact of emissions on the ecosystem, the environment and human health has been growing in the USA since the early 1970s.

Congress set the stage for policy innovation by passing the National Environmental Policy Act at the end of 1969. It called for a national policy to protect the environment and reduce pollution to non-threatening levels. This effort was followed by a spate of Federal enactments in other areas. These include major laws on air and water pollution control, solid waste recovery, pesticide and toxic substance regulation, resource conservation, noise abatement, ocean dumping, coastline management and protection of endangered species.[17] States have also passed legislation to supplement or enlarge the scope of some of these regulations, where necessary.

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[14] Besides air pollution and greenhouse gases, there are externalities that impact water and land use as well. These are not discussed here. *See* Oak Ridge National Laboratory and Resources for the Future, US-EC Fuel Cycle Study: Background Document to the Approach and Issues, ORNL, TN (Nov. 1992).

[15] The data include estimates of emissions from steam electric generating unit plants of 10 MW and more. Emission estimates from gas turbine and internal combustion units are thus excluded. *See* Energy Information Administration, Electric Power Annual 1993, DOE/EIA-0348(93), Washington, DC (Dec. 1994) 71–85.

[16] Council on Environmental Quality (CEQ), Environmental Quality — 1993, Government Printing Office, Washington, DC (1995) 435–441. Within the CEQ's accounting framework — as stated in the National Environmental Policy Act of 1969 — CO_2 emissions statistics are not required. Data on CO_2 emissions for the economy as a whole and for the electricity sector are compiled separately by the Energy Information Administration in terms of the provisions of the Energy Policy Act of 1992. *See* Energy Information Administration, Greenhouse Gases in the United States: 1987–1992, Washington, DC (Nov. 1994). PM_{10} refers to particulate matter of less than 10 μm in diameter.

[17] A summary of major Federal environmental laws affecting the electric utilities is provided in Table A in the Appendix.

TABLE II. EXTERNALITY VALUES FOR DIFFERENT POLLUTANTS, BY STATE (US $ (1992) per ton)

State	Pollutant					
	SO_2	NO_x	TSP[a] or PM_{10}	VOC[b]	CO_2	CO
California	4486	9120	4608	4236	9	NVS[c]
Massachusetts	1700	7200	4400	5900	24	960
Minnesota	150	850	1274	1190	9.8	NVS
Nevada	1716	7480	4598	1012	24	1012
New York	1437	1897	333	NVS	1	NVS
Oregon	0	3500	3000	NVS	25	NVS
Wisconsin	NVS	NVS	NVS	NVS	15	NVS

[a] TSP = total suspended particulates.
[b] VOC = volatile organic compounds.
[c] NVS = no value stipulated.

Notes: Not all pollutants are included in this table. For example, methane and nitrous oxide are not included. Median values are given if the State has a range of values.

Source: Oak Ridge National Laboratory, The Effects of Considering Externalities on Electric Utilities' Mix of Resources: Case Studies of Massachusetts, Wisconsin and California, ORNL, TN (July 1995).

Environmental aspects of power generation activities in the USA are currently governed and directed by both Federal and State regulatory authorities. Federal regulations are often in the form of command-and-control directives. The cost of compliance becomes a part of the cost of power generated for sale to consumers. In this manner, the cost of compliance with Federal regulations is internalized in the price of electricity.

State approaches to handling externalities associated with power generation are recent and do not aim at achieving the optimal regulation necessary to encompass all stages of a fuel cycle. Rather, the States' regulatory efforts are limited to possible investment choices that the utilities need to make when considering capacity additions as part of their resource planning operations. Support for this approach stems from the inherent weaknesses of the traditional least-cost planning approach and the anticipation of stringent environmental controls in the future.

Note that identifying, valuating and determining environmental costs represent a set of controversial issues that are still being debated. Therefore, the initial conceptual framework for including externality costs in power generation focuses only on those externalities (or damages) that can be directly attributed to power generation. As a result, the role of the State regulatory authorities is rather limited in its scope and does not really require the utilities to fully internalize externalities. In addition, the process generally excludes the valuation of health risks, transboundary or site specific issues and the treatment of uncertainties.

4. CANDIDATE STATES FOR CASE STUDIES

Not all State regulatory authorities in the USA require electric utilities in their jurisdiction to take account of externalities in the resource planning process. In fact, only a few of the States attach monetary values to externalities that need to be incorporated in resource planning (Table II).[18] Of these States, Massachusetts, Wisconsin and California were selected for the case studies. Besides providing a balanced representation of diverse regions in the USA, these States had:

— Specific monetary values for externalities (Table II);
— Regulations in place for at least a few years prior to the study so as to allow them to have had some effect;
— Extensive public discourse on the subject during the course of public hearings, studies and other discussions of the issue.

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[18] A total of seven States used monetized externality values: California, Massachusetts, Minnesota, Nevada, New York, Oregon and Wisconsin. Overall, slightly more than half of the States consider externalities, either qualitatively or quantitatively.

An analysis of the regulatory activities of these States with respect to the treatment and incorporation of externalities was supplemented with feedback provided by the largest utility in each State. The intent was to analyse how the electric utilities applied the externality requirements in their integrated resource planning process/analysis and the extent to which these externality values had any effect on the planning process of the utilities.

4.1. The Massachusetts case study

In December 1989, the Massachusetts Department of Public Utilities (MDPU) directed the electric utilities in the State to include an environmental externality component in their all-resource solicitation criteria. The MDPU also defined the cost of externalities "as the costs of environmental damages caused by a project or activity for which compensation to the affected parties does not occur, regardless of whether the costs are imposed within Massachusetts borders or elsewhere".

A procedural debate in subsequent years examined methodological issues associated with externality valuations. After a careful evaluation of the available options, the MDPU finally decided in 1990 to monetize externality values, i.e. to express them in dollars. Dollar valuations were established for nitrogen oxides, sulphur oxides, volatile organic compounds, total suspended particulates, carbon monoxide, carbon dioxide and others. The values determined were to be used in the selection of required resources within the framework of the State's integrated resource management (IRM) process (which treats the supply and demand side options on a consistent basis).

Within a year after the externality values were put in place in Massachusetts, one of the utilities in the State, the Massachusetts Electric Company, submitted its integrated resource management plans by incorporating a set of externality values completely different from those that had been agreed upon. To consider these changes carefully, the MDPU opened a reinvestigation of the proceedings to evaluate whether changes in externality values were called for. The reinvestigation process did not find any reason to modify the externality values it had determined earlier. This decision was released by the MDPU in November 1992.

Since then, the electric utilities in Massachusetts have had only one occasion, in 1994, to file integrated resource management plans that incorporate the reaffirmed externality values. From among these, the plan filed by the New England Electric System (which forms the largest electric utility in the State) provides a good example of the issues considered; it includes the following information:

(a) A forecast of demand and energy use by retail customers;
(b) An inventory of existing resources;
(c) Identification of future resource needs;
(d) A projection of significant new supply side commitments and other new resource additions;

(e) A projection of demand side resources to be developed;
(f) Plans for compliance with new environmental requirements;
(g) A two-year plan for implementing the integrated resource plan;
(h) Any other information required by State laws.

In addition, the plan of the New England Electric System takes into account various environmental requirements, including externality values and concerns about climate change issues. This utility also submitted what it termed a 'Green RFP'[19] to permit an accelerated penetration of renewable resources. This submission was prompted by the possibility of more stringent environmental regulations in the future, which would mean that the choice of renewable technologies now would make them competitive in the future.

Since the 1994 plans were submitted, the Massachusetts programme has suffered a setback. The Supreme Judicial Court of the Commonwealth of Massachusetts issued a decision in December 1994 that the decision by the MDPU on the value of environmental externalities was beyond the range of its statutory authority. The result of the Court's decision is that electric utilities in the State are no longer required to consider monetary externality values in their resource planning until such time as the MDPU issues a decision that this requirement is within its legal authority. An order issued by the MDPU in June 1995 contains revised integrated resource planning procedures but does not embody MDPU's externality policy.

In view of this recent history, it is possible to gain the impression that consideration of environmental externalities is no longer required. However, there is still the requirement for each utility to present evidence that it has taken potential environmental costs into account in its resource planning process.

4.2. The Wisconsin case study

The Wisconsin Public Service Commission (WPSC) maintains that it made an early start in considering environmental concerns, beginning with the enactment of the Wisconsin Environmental Policy Act of 1971, which was followed by the Power Plant Siting Law in 1975. The WPSC maintains that plans (called the Advance Plans or APs) submitted by the utilities since 1978 have taken into account environmental considerations of one kind or the other. In 1980, it was recognized that the impacts of air pollutants (i.e. externalities) were costs that were not reflected in the standard cost/benefit analysis. Subsequent APs took other externalities into account. The AP4, submitted in 1986, directed the utilities in the State to submit future plans using 'integrated resource planning' so that costs and benefits, including those that are 'not easily expressed in dollars', could also be included.

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[19] RFP = request for procurement.

In 1989, the WPSC directed the utilities to incorporate environmental costs in the evaluation of resource options. Specifically, the utilities were required to apply a 15% 'non-combustion' credit to ways of satisfying demands that do not involve the burning of fuels. The directive's intent was to reflect the higher environmental costs of electricity generating options that burn fuels such as coal so that demand side resources and renewable technologies could be promoted. Critics point out that this requirement had little impact on the utility plans since it was not enough to overcome the private cost disadvantages of non-combustion options.

Recognizing that there are externalities other than those caused by combustion, the WPSC directed that the utilities develop methods to permit inclusion of other externalities in the APs. While various methods to achieve this were advanced and debated, the WPSC decided that monetization represented the most straightforward method. Accordingly, the WPSC set monetized values for greenhouse gas emissions in the belief that such emissions would become subject to national or international regulations. The WPSC values are: CO_2 — US $15 per ton, CH_4 — US $150 per ton, NO_x — US $2700 per ton. Utilities in Wisconsin are required to use these values in comparing demand side management programmes and in determining the economic cost of resource options in their planning process.

One reason why the order of WPSC is limited to the consideration of future risk is that there is significant controversy over its authority in the area of air pollution. Incorporation of externalities in the planning process provides a means of accurately accounting for the total cost of a resource option so that its costs and benefits can be compared.

Electric utilities in the State of Wisconsin are required to undertake integrated resource planning jointly and to submit the joint plan to the WPSC. The joint plan contains projections of Statewide demand for electricity over a 20 year planning horizon together with recommendations with respect to capacity acquisitions. The plan also addresses major issues such as cost, reliability and efficiency; and health, safety and environmental effects of various plans for meeting the future electrical needs of the State. In addition to the submission of the joint plan, each utility is required to submit its own individual plan to the WPSC. Monetized values are used in evaluating demand side management potential and supply side resources, including renewable technologies.

The experience of the largest utility in the State, Wisconsin Electric, shows that natural gas will be the fuel of choice for most of the new capacity in the future. Natural gas would replace planned coal capacity additions that were envisaged in an earlier plan. New renewable capacity is not indicated based on its current costs. Nevertheless, the utility plans to bring some renewable capacity on line for reasons other than economic cost considerations (including externalities). The utility's logic is that future improvements in technology and reductions in cost may make renewable technologies more attractive. Overall, externality considerations did not lead to any significant changes in the resource acquisition plans of Wisconsin

Electric. The utility is implementing some voluntary programmes to offset its greenhouse gas emissions.

4.3. The California case study

The State of California has some of the highest levels of pollution in the USA. The State adopted its own Clean Air Act in 1988 to address the unique air quality problems facing California and to establish procedures to attain ambient air quality standards. The State's environmental regulations deal with emissions from power plants as well as emissions from other sources such as automobiles and industrial facilities. Controlling power plant emissions, therefore, constitutes a vital part of the State's strategy in meeting the air quality regulations.

In its 1990 report, the California Energy Commission (CEC) indicated several options that could be used to improve quality and to promote power plant efficiency. Some of these included:

(a) Retrofitting existing facilities, replacing them with cleaner and more efficient gas fired units, or substituting them with non-emitting sources such as demand side management or renewables;
(b) Placing a monetary value on in-State and out-of-State residual emissions for each major pollutant associated with energy generation;
(c) Initiating a market oriented approach so that new facilities could acquire emission reduction credits or offsets (at a price) to prevent an increase in actual emissions (where necessary).

The CEC also directed that all costs and emission impacts resulting from compliance with air quality regulations be accounted for in an analysis of the cost effectiveness of power generation. This approach would permit minimizing the cost of electricity to society as a whole. Necessary legislative enactments were also put in place to empower the CEC and the California Public Utility Commission (CPUC) to initiate appropriate actions in these areas.

The CEC continued grappling with the question of valuation of emissions. The following observations, among others, appeared in its 1990 report:

— Low emitting technologies and renewables have a role to play in reducing emission levels;
— A set-aside for renewables is warranted for a portion of the new capacity;
— Development of an emissions trading programme is considered to be the most effective way to include the value of pollution costs in society's decisions;
— Pending development of the emissions trading programme, residual emission values would continue to be estimated, applied and included in the resource planning decisions.

The CEC recently noted that externality values have had a negligible impact on the actual procurement and operations decisions of the utilities. This result is attributed to uncertainties in the analysis of externalities. Some of the alternatives that the CEC has considered include marketable permits, environmental performance standards, emission taxes and surcharges, and other methods of evaluating externalities. In the view of the CEC, these approaches may permit 'internalization' of externalities. Until this is achieved, its second-best approach is to use set standards as interim measures.

Even though the California utilities broadly support the views of the CEC, Pacific Gas and Electric Co. — the largest utility in the State — contended that most emissions in California are attributable to small, unregulated, or mobile sources. Consequently, piecemeal internalization of externalities might run the risk of a net decrease in benefits.

The CEC staff, however, continues to recommend minimizing social cost as an appropriate goal, regardless of changes likely to occur in the electric utility structure. Since a more competitive industry may limit the capability of the regulators to achieve this goal, the CEC requested that the State legislature establish a collaborative task force to examine the question of externalities in a restructured industry.

The CEC has also specified externality values for certain categories of emissions, including carbon dioxide. These externality values are based on the estimates of the marginal cost of the best available control technology. The values differ from region to region within the State, depending on the region's level of air quality attainment and the service area.

Note that the values recommended by the CEC are not binding on the CPUC, which is the regulatory authority in the State that implements the incorporation of externality values by the electric utilities. The CPUC, therefore, makes its own determination of the externality values to be used.[20]

The most recent Electric Resource Plan submitted by Pacific Gas and Electric Co. relies on three elements:

— Cost-effective demand side management,
— Efficient use and maintenance of existing resources,
— Flexible new contracts in the wholesale market for power.

In addition, the 1994 plan calls for economic upgrades, licence extensions and environmental retrofits. The forecasted date for new supply resources is 2002. The utility's analysis shows little impact on the mix of resources as a result of externality considerations.

[20] For this reason, the externality values used by Pacific Gas and Electric Co. differ somewhat from the values shown in Table II.

5. CONCLUSIONS

Analysis of the reports from the State regulatory authorities and the utilities in Massachusetts, Wisconsin and California indicates that the requirement to incorporate externalities in the resource planning process had negligible impacts on the resource mix of the utilities in each of the three States. As a result of calculations using the prescribed externality values, no renewable energy technology was selected. The scope of demand side management activities was also largely unaffected by externality considerations. These findings are not surprising, for the following reasons:

(a) There has been little need for new capacity;
(b) Utilities have little experience with renewable technologies (other than hydroelectric power) and are more apt to purchase a financial interest in an existing project than to build a new one;
(c) Where utilities operate in more than one State, inter-jurisdictional issues make it difficult for utilities to secure concurrences from all regulatory authorities;
(d) Where limited choices have been made, natural gas has emerged as the fuel of choice because of an ongoing decline in its price.

The electric power industry in the USA has been undergoing changes since the mid-1970s. Regulatory changes initiated by the Public Utility Regulatory Policies Act (PURPA) of 1978 accelerated changes in the industry. By permitting the entry of non-utility generators in the field of power generation, PURPA launched a process that facilitated penetration of the power generation monopoly enjoyed by the vertically integrated utilities. Subsequent enactment of the Energy Policy Act of 1992 has quickened the pace of transition and potential restructuring (by fostering competition in the industry) to a level that could not possibly have been envisioned a few years earlier.[21] The speed and the progress of evolutionary changes will depend on various factors that may not be resolved in the near future.

[21] Provisions of the Energy Policy Act of 1992 (EPACT) spur competition by creating a new category of power producers, called exempt wholesale generators. EPACT also requires all utilities that own transmission facilities to grant non-discriminatory access to transmission grids and empowers the Federal Energy Regulatory Commission to ensure that utilities do provide this access.

A likely consequence of the restructuring would be the erosion of vertically integrated electric utilities, with a significant dispersion of generation activities implicit in the unbundling of the services concept.[22] With the availability of transmission access, the customers are expected to have the freedom to go to any supplier of their choice, based on considerations of price and service.[23]

A dispersion of generation activities may imply fundamental changes in the exercise of regulatory oversight in the future. Some of the existing regulations may need to be modified and some new guidelines may still be necessary. In this environment, the State regulatory authorities may no longer be in a position to exercise control over acquisition of supply side resources within the existing regulatory framework. The capability of States to enforce a consideration and incorporation of externalities — in its current mode — may no longer be feasible.

As restructuring progresses, issues other than environmental externalities may become more critical for the regulatory authorities. Issues connected with handling of stranded investments, divestiture of generation facilities, transmission access and its pricing are possibly going to occupy the centre stage in the near future. The primary concern of State regulatory authorities would be to ensure reliability of services at reasonable prices for power. The possibility that environmental considerations, by the States, may be placed on the backburner is, therefore, not unlikely.

Even where the States manage to remain proactive in the handling of externalities, the impact scenario based on recent experience is far from encouraging. In addition, the State regulatory authorities can operate only within the State boundaries, whereas the environmental impacts of electricity generation inflict transboundary damages. Finally, energetic pursuance by regulatory authorities of handling externalities could, in theory, raise electricity prices to levels higher than those prevailing in neighbouring States if an approach similar to that in these States is not pursued. The economic consequences of this disparity may imply that States may be reluctant to lose their competitive advantage.

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[22] Vertically integrated electric utilities currently provide bundled services to their customers who treat and pay for electricity as a single, homogeneous product. Their tariff structure bundles the cost of generation, transmission, distribution and other ancillary services. Industry restructuring (in the future) may necessitate unbundling, implying a realignment of traditional assets currently included in the rate base along functional lines. Realignment of assets may be through sale, segregation, divestiture, changes in corporate ownership, or a shifting of assets outside the rate base. Asset realignment may, therefore, lead to specific services being charged separately.

[23] The report does not discuss other consequences or ramifications of industry restructuring. It is worth while noting, however, that there will be significant changes concerning industry regulation in the future.

However, the future may be less bleak than is commonly envisaged. It should be recognized that both the regulatory authorities and the utilities are sensitive to the risks of environmental damage and the role that less polluting fuels or renewable technologies can play in the future. Innovative options for effectively treating externalities could still be found within an industry structure that may not be vertically integrated. A review of the recent State proceedings and other forums indicates that there is considerable support for addressing 'potentially strandable benefits' such as environmental protection, energy efficiency and renewable energy. There is interest in explicitly designing environmental and other public interest considerations into the electric industry framework, as is evident from the proceedings in Massachusetts and California. As a result, it may be difficult to predict the future of externality consideration in State settings.

Appendix

TABLE A. MAJOR FEDERAL ENVIRONMENTAL LAWS AFFECTING ELECTRIC UTILITIES

Legislation	Brief description of impacts on electric utilities
The Federal Power Act of 1920 (amended by the Electric Consumers Protection Act of 1986)	The Federal Power Act (FPA) provides the Federal Energy Regulatory Commission (FERC) with exclusive authority to license non-Federal hydroelectric power projects on navigable waterways and Federal lands. The Electric Consumers Protection Act amended the FPA in 1986 and required FERC, during its licensing/relicensing activities, to accord equal consideration to environmental aspects of hydroelectric facilities in addition to an evaluation and determination of a number of other factors such as power development and public interests. Environmental considerations include the protection, mitigation of damage to, and enhancement of, fish and wildlife; the protection of recreational opportunities; and the preservation of other aspects of environmental quality.
The Federal Water Power Act of 1920	The Federal Water Power Act authorized the Federal Power Commission, the precursor agency of FERC, to license certain hydroelectric projects that are best adapted to the comprehensive development of a waterway. The responsibilities of FERC in regard to overseeing the development of US water resources were broadened under later legislation including the Flood Control Act of 1938 and subsequent Flood Control Acts; the River and Harbor Act of 1945 and subsequent River and Harbor Acts; and the Water Resources Planning Act of 1965.

The Fish and Wildlife Coordination Act of 1934 (amended in 1946, 1948, 1958 and 1965)	The Fish and Wildlife Coordination Act requires that a Federal agency licensing a 'water resource development project' consult with and give full consideration to the recommendations of the Fish and Wildlife Service under the Department of the Interior. In addition, FERC must include conditions in each licence for the protection, mitigation of damage to, and enhancement of, fish and wildlife.
The Atomic Energy Act of 1954 (amended by the **Energy Reorganization Act of 1974)**	The Atomic Energy Act (AEA) was first enacted after World War II to give the Federal Government direct control over the development of nuclear power. Congress revised the Act in 1954 to allow for licensing private facilities. The regulation of power plant licensing and siting under the AEA presents significant public policy and legal issues. Environmental and safety considerations are an important element of the licensing process for nuclear power plants. This regulatory responsibility was transferred to the Nuclear Regulatory Commission (NRC) in 1974 when Congress enacted the Energy Reorganization Act, which abolished the Atomic Energy Commission. The NRC has the responsibility for licensing and monitoring nuclear reactors and waste facilities, inspecting nuclear facilities and investigating nuclear accidents.
The Clean Air Act of 1963 (amended in 1967, 1970, 1977 and 1990)	The 1963 Clean Air Act (CAA), as amended, established a major regulatory system to protect and enhance the Nation's air that is directly applicable to conventional electric power generation facilities. National ambient air quality standards were put into effect for particulate matter, sulphur dioxide, nitrogen dioxide, carbon monoxide, ozone and lead. Of these, particulate matter, sulphur dioxide and nitrogen dioxide are emitted in significant quantities by coal fired electric power plants. The 1990 amendments to the CAA in large part were intended to meet unaddressed or insufficiently addressed problems such as ground-level ozone, stratospheric ozone depletion, air toxins and acid rain, the last of which was directly addressed through the Acid Rain Program.

TABLE A (cont.)

Legislation	Brief description of impacts on electric utilities
The Wild and Scenic Rivers Act of 1968	The Wild and Scenic Rivers Act prohibits FERC from licensing construction of any project under the Federal Power Act "on or directly affecting" a wild and scenic river. In addition, it limits the power of any Federal agency to assist in the construction of any "water resources project" having a "direct and adverse effect on the values" for which the river was designated as wild and scenic.
The National Environmental Policy Act of 1969 (amended in 1975 and 1982)	The National Environmental Policy Act of 1969 (NEPA) requires all Federal agencies to prepare a "detailed statement" for proposed major actions that significantly affect the quality of the human environment. This statement, called an "environmental impact statement (EIS)", must include environmental impacts of the proposed action, alternatives to the proposed action, and any adverse environmental impacts that cannot be avoided should the proposal be implemented. Thus, in effect, where a permit or a licence is required for the construction of power plants or associated facilities under Federal law, an EIS is usually necessary. The NEPA does not include all actions taken by electric utilities. It may exclude, for example, the construction of fossil fuel plants. However, the EIS process may still be triggered if such plants involve Federal approval of any related matter.
The Endangered Species Act of 1973	The Endangered Species Act of 1973 provides a programme for the preservation of threatened plants, fish and wildlife, and the habitat in which they are found. The building of dams for hydroelectric power generation can disrupt the ecological environment and, therefore, must adhere to regulations under this Act.

The Safe Drinking Water Act of 1974	The Safe Drinking Water Act of 1974 (SDWA) specifies that any business that has 25 or more employees and is not on a public water system must ensure that its source of drinking water complies with certain primary health related standards.
The Toxic Substances Control Act of 1976	The Toxic Substances Control Act of 1976 (TSCA) requires proper disposal of polychlorinated biphenals (PCBs) and prohibits their manufacture, processing, distribution in commerce, and use in other than a totally enclosed manner. PCBs were used for many years in electrical equipment, i.e. in the dielectric fluid used in transformers. The Environmental Protection Agency (EPA) subsequently adopted rules governing the marking and disposal of PCBs and adopted regulations prohibiting and restricting their continued use. Although a number of statutes regulated chemicals after they had become 'wastes' or 'discharges', no legislation regulated hazardous and toxic substances (other than those used in food or drugs) before they were wastes. TSCA empowers EPA to manage the manufacture and use of toxic substances. TSCA also allows EPA to monitor new or existing chemicals that pose an unreasonable risk to health or the environment.
The Resource Conservation and Recovery Act of 1976 (extensively amended by the **Hazardous and Solid Waste Amendments of 1984**)	The Resource Conservation and Recovery Act of 1976 is a statute designed to provide 'cradle-to-grave' control of hazardous waste by imposing management requirements on generators and transporters of hazardous wastes and on the owners and operators of treatment, storage and disposal facilities. The disposal of certain waste by electric utilities may be subject to provisions of this Act. The utilities must comply with a set of standards authorized under this Act, including handling wastes properly and preparing manifests to track the shipment of the waste to treatment, recycling or disposal facilities. EPA's regulations automatically exempt utility wastes from coal combustion from being considered hazardous wastes.

TABLE A (cont.)

Legislation	Brief description of impacts on electric utilities
The Clean Water Act of 1977 (amendment to the **Federal Water Pollution Control Act of 1972**)	States were responsible, before 1970, for setting their own water quality standards. Congress, however, in 1972, established the Federal Water Pollution Control Act. Congress, in 1977, modified the Act to deal with other pollutants and renamed it the Clean Water Act (CWA). The CWA established a system for setting national effluent standards for pollutant discharges and a national water discharge permit programme. The CWA affects various types of electric power facilities in a significant way. Use of large amounts of water for steam to drive turbines, for cooling, and for process uses in conventional power plants and nuclear power plants raises potential water issues. Similarly, the proximity to and dependence of hydroelectric facilities on flowing water as a source of power also raise potential water issues. Thus, electric power facilities can be subject to various obligations, including requirements to obtain operating permits and to meet the best available technology standards to minimize adverse environmental impacts.
The Comprehensive Environmental Response, Compensation and Liability Act of 1980 (also referred to as **Superfund**)	Electric utilities are among many business establishments that are subject to reporting requirements for spills and other kinds of environmental releases under the Comprehensive Environmental Response, Compensation and Liability Act of 1980. Utilities must report any release of any hazardous substance that exceeds the reportable quantity for that substance (defined in Title 40 of the Code of Federal Regulations) into the air, surface water, groundwater or soil.
The Nuclear Waste Policy Act of 1982	The Nuclear Waste Policy Act of 1982 (NWPA) specifies that, while the Federal Government has the responsibility to provide for the disposal of high level radioactive waste and spent nuclear fuel in order to protect public health and safety and the environment, generators and owners of the waste and spent fuel have the primary responsibility to provide and pay for its interim storage. The NWPA also establishes procedures for disposal site selection,

	licensing, construction, closure, decommissioning, interim storage licensing, and retrieval of any spent nuclear fuel, for reasons associated with public health and safety, the environment, or the recovery of the economically valuable contents of the spent fuel.
The Energy Policy Act of 1992	The Energy Policy Act of 1992 (EPACT) contains various environmental provisions with respect to global warming issues. While there are no mandatory requirements affecting electric utilities, voluntary reporting of greenhouse gas emissions and reductions will be used by the DOE to develop an inventory of the national aggregate emissions of each greenhouse gas for each calendar year of a baseline period. This inventory will be updated and analysed annually. EPACT also requires DOE to study and implement water conservation measures at Federal water projects to provide more water for fish and wildlife. In addition, EPACT contains numerous provisions designed to foster development of renewable energy technologies that contribute little to smog, acid rain, or greenhouse gas emissions.
The Wilderness Act of 1964 **The Historic Preservation Act of 1968** **The Water Quality Improvement Act of 1970** **The Coastal Zone Management Act of 1972** **The Federal Land Policy and Management Act of 1976**	Potential hydroelectric power generation projects may be constrained by these miscellaneous laws if certain associated environmental regulations apply.

Note: Following general practice, the term 'regulation' used in this table includes laws that engender Federal regulations. Accordingly, the terms 'regulation(s)' and 'law(s)' are used interchangeably. This section is based on information compiled from various documents, including Congressional Quarterly and the Environmental Law Reporter, as well as others published by the following organizations: the Environmental Protection Agency, the Congressional Research Service, Government Institutes, Inc., the Environmental and Energy Institute, the Environmental Law Institute, the Council on Environmental Quality and the Federal Energy Regulatory Commission.

THE CO2DB INVENTORY AND ITS APPLICATION IN A COMPARATIVE ASSESSMENT OF ELECTRICITY END USE OPTIONS

S. MESSNER
International Institute for Applied Systems Analysis,
Laxenburg, Austria

Abstract

THE CO2DB INVENTORY AND ITS APPLICATION IN A COMPARATIVE ASSESSMENT OF ELECTRICITY END USE OPTIONS.

The greenhouse gas mitigation technology inventory developed at the International Institute for Applied Systems Analysis over the last five years, CO2DB, its software capabilities and the present coverage of technologies are discussed. For some clusters of the more than 1400 technologies represented in the database, the frequencies of investment estimates are analysed. The special capability of CO2DB to evaluate full energy conversion chains, from primary extraction to final utilization of energy, is applied in a comparison of various options to reduce the CO_2 emissions related to a specific application of electricity. This evaluation proves useful in the numerical comparison of the cost of reducing CO_2 emissions by various technological options.

1. INTRODUCTION

The research project on environmentally compatible energy strategies (ECS) at the International Institute for Applied Systems Analysis (IIASA) focuses on formulating long term options and strategies for environmentally compatible energy development. In particular, the objective of this project is to assess future potentials and rates of worldwide reduction of energy and carbon intensity. Figure 1 presents data on historical improvements in CO_2 emissions achieved in a number of selected countries [1]. It is intended to analyse the trajectories of future options that would lead individual countries and the world as a whole further towards lower specific CO_2 emissions per unit value added, as shown for the historical changes in Fig. 1. Some countries having similar levels of affluence emit less CO_2 and others emit more CO_2, indicating that decarbonization and development do not exclude each other, provided an appropriate policy mix is found. Especially striking is the large 'north–south' disparity in energy related CO_2 emissions. The burden of developing countries is twofold: they need to increase the per capita energy consumption in order to improve the quality of life of their population, but they are also more vulnerable to adverse consequences of climate change. Industrialized countries are in a better position to achieve reductions of emissions and they can also better respond and adapt to climate change.

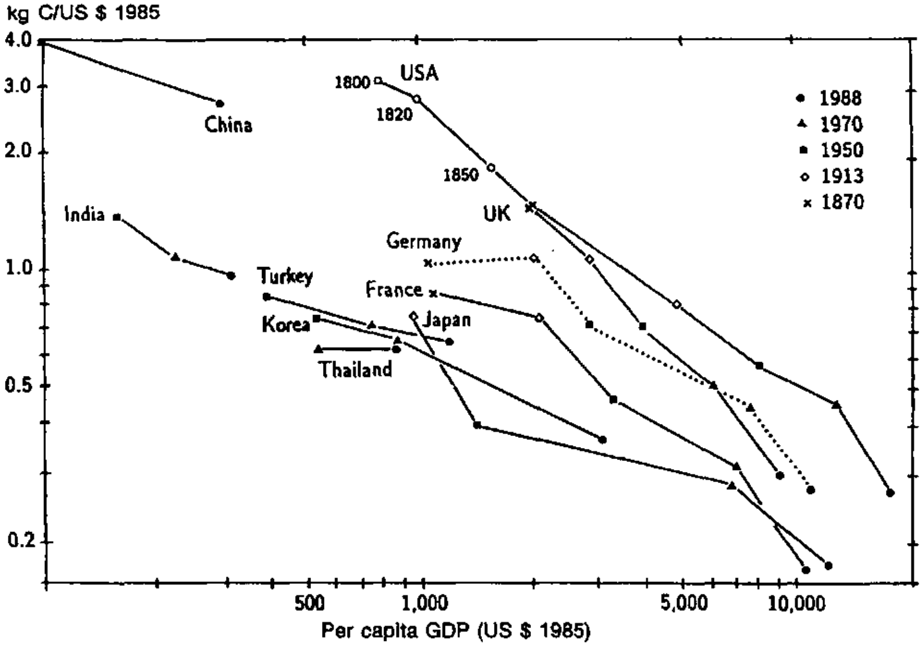

FIG. 1. Intensity of CO_2 emission per constant GDP, in kg carbon per constant 1985 US dollars, versus per capita GDP in constant 1985 US dollars.

These considerations suggest that, in the absence of appropriate countermeasures, global emissions of greenhouse gases will continue to increase well into the 21st century, perhaps beyond environmentally acceptable levels. A comparative assessment of different options and strategies for mitigating and adapting to possible global warming is therefore required. A focal point of the research project at IIASA is a comprehensive assessment of a broad range of options needed for evaluating the global potential for stabilizing the level of CO_2 and other greenhouse gases, and ultimately reducing and perhaps even removing these gases from the atmosphere [2]. This research effort involves the development of an inventory of technologies for reducing CO_2 emissions — the CO2DB. Applications of CO2DB are reported in Refs [3–5].

2. OVERVIEW OF THE CO2DB TECHNOLOGY INVENTORY

The CO_2 mitigation technology database CO2DB is a fully interactive software package designed to allow the user to enter, update, view and print information about energy technologies [6]. The CO2DB software utilizes the commercially available database system db_VISTA.[1] This system is based on the network databank model, which makes it a flexible programming tool with easy access to large volumes of data. It also supports functions of the relational databank model and the SQL standard queries. The code is written in C language and runs under MS-DOS. Screen control is performed with CURSES; the menus were designed with the menu generator FAST.[2]

Special features allow the user to select technologies conforming to predefined criteria for further processing; to calculate the overall efficiency, cost and environmental effects of energy conversion chains; to store additional information on computer files using the system editor; and to exchange technology data over different operating systems using the import and export facility. Currently, more than 90 institutions operate worldwide on CO2DB databases.

The structure of the databank system reflects the data requirements that are essential to the CO_2 problem. Each technology is described by seven data categories (called tables according to the standards of the databank):

The General Data Table describes the technology by the following items:

— Identification of the technology; this includes the full name, a short identification, general notes and an item assessing the data quality;
— Names of the physical file (paper) and the computer file containing additional information (graphs, process flow charts, descriptions, etc.);
— Definition of the life cycle phases and the market penetration rates of this technology (stating the years of invention, innovation, first prototype, 1% and 50% market penetration, and giving a description of the present life cycle phase); the life cycle concept and related data can be used to evaluate the timing and dynamics of the market penetration of the technologies;
— Categorization of the technology with respect to four categories (sector, type, input and output); the categorization serves as a basis for aggregating the technologies into groups for reporting and evaluation. The definition of input and output is used to interlink the technologies in the evaluation of energy chains.

The Technical Data Table contains information on the physical energy flows in the process (quantities of energy inputs and outputs), and information on unit size, technical and average availability, construction time and plant life.

[1] db_VISTA is a product of Raima Corporation, Bellevue, WA, USA.

[2] FAST and CURSES for MS-DOS are products of Aspen Scientific, Wheatridge, CO, USA.

The information on physical energy flows defines the efficiency of the technology and consequently the performance, e.g. in the context of reducing primary energy consumption without lowering the services provided. In the context of evaluating complete energy conversion chains from primary energy to energy services, the energy carriers in the technical description provide the linkage.

The Economic Data Table describes the economic characteristics of the technology. It includes investment, fixed and variable operating and maintenance costs, fuel and decommissioning costs, as well as the resulting total costs. The currency and year of the estimates must be supplied.

Although it is questionable whether it is possible at all to estimate future economic technology characteristics, especially over a period of a century, such estimates are nevertheless useful in ranking future technology performance and in obtaining time profiles for investment, operating costs, etc.

The Environmental Data Table identifies the emission of pollutants (or means of their disposal) during the operation of a facility. This table also contains the quantity of a pollutant removed from the atmosphere, soil or water by reduction and control measures. The environmental parameters are essential to evaluating the impacts of CO_2 reduction strategies, their effectiveness and potential side-effects.

The Labour and Material Requirements Table contains the labour and material requirements for construction and operation of a facility. These data are required to formulate broader conditions and limiting factors for the application of technologies. Labour and material requirements need not be specified for technologies in the normal range of these values.

The Miscellaneous Data Table includes regional characteristics of the technology application as well as prerequisites and limitations of its use. Additional information on present research activities and producers, and on the number and capacity of existing units can be given.

Although these data are generally not derived from practice, but rather represent personal estimates of future border conditions (together with the market penetration characterization in the General Data Table), the items defined in this table are a cornerstone in the evaluation of market potentials and the introduction of new technologies. This table specifies all considerations regarding technological diffusion and technology transfer, prerequisites for the introduction of a technology, and the timing of the introduction of a technology in a given region. In the refinement process, initial crude estimates or purely qualitative statements can contribute to the limiting factors applied in the final evaluation of technological strategies.

The Literature Table provides the basic references used to compile the information on the technology. It includes the title, author(s), publisher, year of publication, and comments on the availability of the source.

3. CO2DB AND ITS RELEVANCE TO ELECTRICITY

In its current version, CO2DB contains information for over 1400 technologies. The technology descriptions in CO2DB cover a wide range of processes related to the extraction, conversion, transport, distribution and final utilization of energy. In the field of energy related investments, electricity clearly holds the most prominent position. This has led the ECS team to place the most emphasis on investigating these technologies, again with the greatest effort on collecting investment figures from as many sources as possible. Table I gives an overview of the types of technologies covered by the present version of CO2DB.

TABLE I. CONTENTS OF CO2DB BY TYPE OF TECHNOLOGY

Technology type	Number	Share (%)
Electricity generation	1045	71.2
Other conversion	88	6.0
Transport and distribution	20	1.4
Final use of energy	205	14.0
Energy supply and imports	99	6.7
CO_2 management	11	0.7
Total	1468	100.0

TABLE II. ELECTRICITY END USE TECHNOLOGIES IN CO2DB BY SECTOR

Sector	Number	Share (%)
Industry	24	19.2
Residential/commercial	60	48.0
Transport	8	6.4
Other technologies	33	26.4
Total	125	100.0

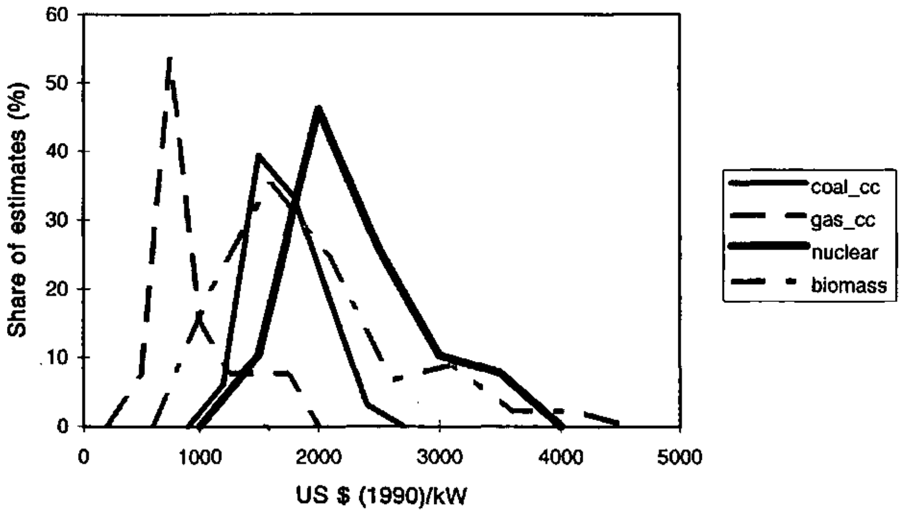

FIG. 2. Frequency distribution of investment cost estimates from CO2DB for coal fired combined cycle power plants (coal_cc), gas fired combined cycle power plants (gas_cc), nuclear reactors and biomass fired electricity generation.

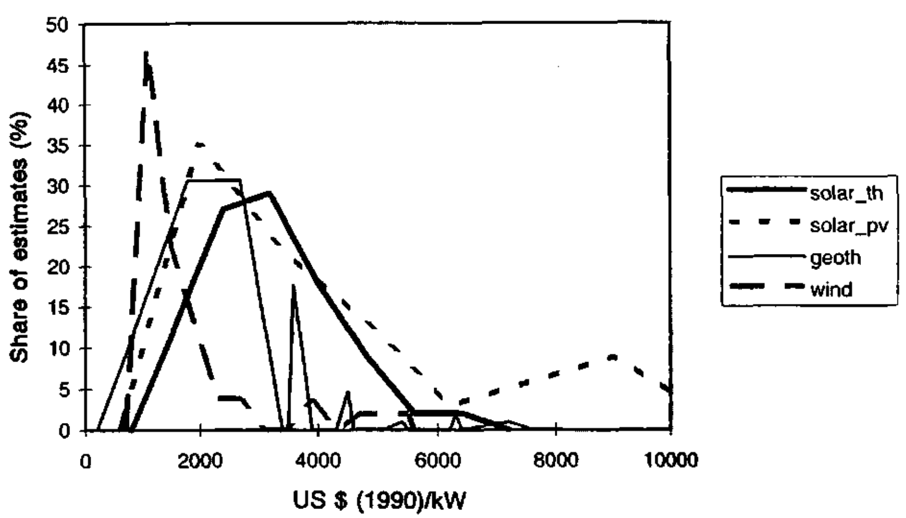

FIG. 3. Frequency distribution of investment cost estimates from CO2DB for thermal solar power plants (solar_th), photovoltaic systems (solar_pv), geothermal electricity generation (geoth) and wind generators.

Electricity generation and cogeneration technologies, with 1045 entries, hold a share of more than 70% of all entries. The second largest emphasis in CO2DB is on utilization of energy, with 205 entries or 14% of all technologies; 125 (61%) of these are electricity end use technologies. Table II gives an overview of the distribution by sector of the electricity end use technologies in CO2DB. Residential and commercial end uses are very well represented by 60 technologies, industrial applications are covered by 24 entries, while the low relevance of electricity use in the transport sector is reflected by the low number of technologies (8). The remaining 33 technologies cover general areas that cannot be attributed to a specific sector, such as lighting technologies or electric motors for mechanical drives. An effort was made to analyse the contents of CO2DB with respect to specific types of technologies, such as normal or advanced coal power plants or nuclear reactors. In this analysis, all literature sources for the technologies investigated were checked in order to identify technology descriptions based on the same data source (i.e. to eliminate double counts). Then, the characteristics of the remaining unique technologies were analysed statistically, as documented in Ref. [7]. An additional outcome of this analysis is the frequencies of various cost estimates concerning the technologies analysed.

Figures 2 and 3 are graphs with frequency distributions of investment cost estimates for various types of power plants. The horizontal axis gives the investment cost of the plants in US $ (1990) per kilowatt; the vertical axis displays the percentage of estimates giving the corresponding cost values.

Figure 2 shows the frequency distribution for coal fired combined cycle power plants (coal_cc) for a range of cost estimates, from US $1000/kW to US $1500/kW; for gas fired combined cycle power plants (gas_cc) with considerably lower costs of around US $750/kW and a very high frequency (>50%); for nuclear reactors with a wider cost range, between US $1500/kW and US $3500/kW; and for biomass fired electricity generation with even lower correspondence among the estimates.

Figure 3 displays the same information as Fig. 2, for renewable electricity generation technologies. For all of them (thermal solar power plants, photovoltaic systems, geothermal electricity generation and wind generators) the estimates with the highest frequencies are at the lower end of the overall range of cost estimates, while there is a rather long tail of high cost estimates.

4. EVALUATION OF SPECIFIC ELECTRICITY CHAINS

One of the features of CO2DB is the capability to evaluate full energy conversion chains with respect to their technical, economic and environmental performance. Outcomes of such analyses are overall efficiency or energy use, system cost and pollutant emissions, all per unit of service supplied. Such analyses are well suited to application in the context of integrated resource planning (IRP), where an integrated approach, including all steps of the energy conversion chain, is applied in the evaluation of different options to supply an energy service.

The following exemplary application of CO2DB investigates different options for the supply of the service of food refrigeration for one typical household for one year. It includes different options of supplying electricity from the same source of energy (hard coal) and contrasts them with investments in more efficient, but also more costly, end use systems. The energy chains analysed include the following technological options, which were derived from Refs [8–10] and from ECS work on technologies.

1. A 500 L combined refrigerator/deep-freeze. Three different models are evaluated:
   - bl: baseline — average technology used,
   - ba: best technology available commercially,
   - adv: advanced technology not yet available commercially.
2. Electricity transmission and distribution: a technology from CO2DB, representing average cost and performance of electricity transmission and distribution.
3. Various types of coal fired power plants:
   - hcpp: pulverized hard coal power plant,
   - hccc: gasified coal combined cycle power plant (an integrated gasification combined cycle, IGCC),
   - mcfc: molten carbonate fuel cell using gasified coal,
   - chabs: power plant using pulverized coal plus CO_2 removal by chemical absorption.
4. Import of hard coal at the average price for Member States of the International Energy Agency in 1990 (US $1.74/GJ).

Table III compares the results of various combinations of the above technologies. The costs are evaluated at a discount rate of 6% and are always given in US $ of the year 1990; the annual energy use and CO_2 emissions are also given. The following two investment categories are opposite to each other: investment in more efficient end use systems, i.e. better refrigerators, and investment in improved power generation. Finally, a combination of advanced end use systems and power generation based on fuel cells yields the most possible reductions in energy and in CO_2.

Advanced power generation technologies, such as the use of IGCC or fuel cells, can reduce the energy requirements by up to 20%, saving the same fraction of CO_2 emissions. On the other hand, more advanced end use systems, which are already commercially available today, would reduce the energy use and CO_2 emis-

TABLE III. ANNUAL COST, ENERGY USE AND CO_2 EMISSIONS FOR THE CHAINS INVESTIGATED

System		Cost	Energy use	CO_2 emissions
Refrigerator	Power plant	(US $ (1990))	(GJ)	(kg)
bl	hcpp	44.6	8.0	790
bl	hccc	45.9	7.5	740
bl	mcfc	54.9	6.5	630
bl	chabs	65.5	11.3	170
ba	hcpp	36.1	5.5	540
adv	hcpp	31.3	2.0	195
adv	mcfc	33.9	1.6	160

sions by one third. The strongest reduction of CO_2 emissions (by 75%) can be achieved by using very advanced end use technology, by scrubbing the flue-gases of the power plant (reduction of 78%), or by a combination of the advanced end use technology and the use of a fuel cell for electricity generation (reduction of 80%).

Table IV shows the absolute change in energy use and CO_2 emissions of the various systems as compared with the first chain in the table. All chains reduce the CO_2 emissions, but the chemical absorption chain increases at the same time the energy use by 3.3 GJ per refrigerator and year. For investments in power plants, energy conservation is achieved with additional costs; for investments in the end use systems, cost reductions can be anticipated (negative costs). In the case of investing in both end use and central conversion, where the highest reduction in energy use can be achieved, the overall cost is still reduced. In the case of scrubbing, where both energy consumption and costs increase, the resulting change in costs per unit of change in energy use is negative, i.e. the user has to pay more for consuming more primary energy.

For investments in power plants the costs of reducing CO_2 emissions are in the range of US $30–60 per tonne CO_2 not emitted; for investments in refrigerators, moderate gains of US $20–30 per tonne CO_2 can be expected.

TABLE IV. CHANGE IN ENERGY USE AND CO_2 EMISSIONS (PER SYSTEM AND YEAR) AND IN SPECIFIC COSTS (REDUCTION) FOR THE CHAINS INVESTIGATED

System		Energy use	CO_2 emissions	Reduction	
Refrigerator	Power plant	(GJ)	(kg)	US \$/GJ	US \$/t CO_2
bl	hcpp	0.0	0.0	0.0	0.0
bl	hccc	−0.5	−50	2.7	26.0
bl	mcfc	−1.5	−160	6.9	64.7
bl	chabs	3.3	−620	−6.3	33.7
ba	hcpp	−2.5	−250	−3.4	−34.0
adv	hcpp	−6.0	−595	−2.2	−22.4
adv	mcfc	−6.4	−630	1.7	−17.1

5. FINAL REMARKS

The CO2DB has proved very useful in evaluating the economics of reducing energy use and CO_2 emissions for energy conversion chains. For a chain providing refrigeration of food for households from coal based electricity, different technologies have been compared. However, a comprehensive analysis on the lines of IRP would require an integrated approach that dynamically compares the various energy supply and utilization technologies available under the conditions prevailing in the energy system. Dynamic optimization models such as MESSAGE III [11], which is applied at IIASA to evaluate energy strategies, are best suited for such analyses. The CO2DB provides valuable background information and the required cost and performance characteristics for such modelling efforts.

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COMPARATIVE ASSESSMENT IN DECISION MAKING

(Session 6)

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ONTARIO HYDRO'S EXPERIENCE IN LINKING SUSTAINABLE DEVELOPMENT, FULL COST ACCOUNTING AND ENVIRONMENTAL ASSESSMENT

C. BOONE, H. HOWES, B. REUBER
Environment and Sustainable Development Division,
Business/Environment Integration Department,
Ontario Hydro,
Toronto, Ontario, Canada

Abstract

ONTARIO HYDRO'S EXPERIENCE IN LINKING SUSTAINABLE DEVELOPMENT, FULL COST ACCOUNTING AND ENVIRONMENTAL ASSESSMENT.

Ontario Hydro's mission is "to make Ontario Hydro a leader in energy efficiency and sustainable development, and to provide its customers with safe and reliable energy services at competitive prices". In April 1995, Ontario Hydro's Board of Directors approved a sustainable energy development (SED) policy, guiding principles and strategic guidelines that elaborate on Ontario Hydro's commitment to sustainable development as expressed in the mission statement. This policy provides the framework for operational sustainable development. One of Ontario Hydro's guiding priniples for SED is integration of environmental and social factors into planning, decision making and business practices. Full cost accounting is a tool used at Ontario Hydro to achieve this integration. Ontario Hydro's approach to full cost accounting has two components: (1) to better define and allocate the internal environmental costs, and (2) to better define and cost the externalities associated with its activities. Three examples are provided of Ontario Hydro's success in integrating environmental considerations into its planning and decision making: (a) A set of SED decision criteria are applied to business case analyses for investment proposals. The SED decision criteria focus on five components for investment decisions: maximizing resource use and energy efficiency, reducing environmental damage/impacts, avoiding/improving social impacts, increasing the use of renewable technologies, and identifying financial gains attributable to sustainable development initiatives. (b) The environmental assessment for the Corporate Integrated Resource Plan was performed on an environmental damage basis consistent with Ontario Hydro's corporate guidelines for full cost accounting. The results of the environmental assessment were combined with fourteen other measures using multicriteria analysis to evaluate alternative system plans. (c) A study was undertaken to examine the potential externalities associated with transmission and distribution of electricity.

1. INTRODUCTION

It has been Ontario Hydro's experience that there is a critical link between environmental assessment and sustainable development. Environmental assessment is one of the cornerstones for both sustainable development and full cost accounting. In fact, Ontario Hydro's current focus on sustainable development builds on a long-standing tradition of commitment to, and practice of, environmental impact assessment.

The environmental consequences of energy production and use must be known in order to manage energy products and services keeping in mind the needs of future generations. Resource depletion and intergenerational equity issues must be addressed. Environmental assessment is also the basis for identifying the environmental impacts associated with the generation or transmission of electricity. Full cost accounting, in particular the focus on externalities, takes these environmental and human health impacts one step further, by quantifying and, where possible, monetizing the damage to the environment and to human health associated with the emission or effluent or waste resulting from electricity production and use. By considering the externalities associated with its activities, Ontario Hydro is making decisions based on least cost to society.

This paper focuses on Ontario Hydro's experience in operational sustainable development and in developing ways to better integrate environmental and sustainable development considerations into its planning and decision making.

2. CONTEXT FOR ONTARIO HYDRO

Ontario Hydro is an electric utility located in Ontario, Canada. It is a public utility which provides about 134 TW·h of electricity annually to approximately four million customers, either directly or through municipal electric utilities. In 1994, approximately 62% of the energy produced was from nuclear stations; 24% from hydroelectric sources; 10% from coal fired plants; about 1.0% was generated from gas fired, private generators; less than 1% from renewable energy technologies (i.e. wind, photovoltaics); and the remainder was from purchases from neighbouring utilities.

As virtually every electric utility in North America, Ontario Hydro has undergone significant change in the last few years. Staff size has been reduced by over 30%. Annual capital budgets have been reduced by over Can$100 million, and several significant restructuring changes have occurred to improve the efficiency and effectiveness of the corporation. The major driver behind these changes has been the need to become more competitive.

3. TOWARDS SUSTAINABLE ENERGY DEVELOPMENT (SED)

One of the major catalysts for these changes was the appointment of a new Chairman, Maurice Strong, in late 1992, who, in addition to his mandate to restructure the corporation, also had a strong focus on sustainable development.

The impetus for Ontario Hydro's current sustainable development (SD) programme was the establishment, by the Chairman, of a Task Force on SED in June 1993. It was led by two recognized Canadian authorities in SD and included senior representatives of the major business units in the company. Their task was to create, in three months, a blueprint to guide the organization in moving towards a sustainable energy future. While it was true that Ontario Hydro was doing many of the right things from an environmental management perspective, and in some areas demonstrating environmental leadership, an SD ethic was certainly not part of its corporate culture.

The recommendations of the Task Force on SED [1] ranged from changes in corporate structure to support SED, to improving the decision making processes to better incorporate environmental factors, to establishing 'green funds' to finance SED initiatives, to developing appropriate SED training, communication and reskilling programmes. The recommendations were assigned to the appropriate Business Unit leaders to implement in 1994.

Many innovative actions were taken in 1994 in response to this new SED challenge. However, the focus of this paper is on only one component of Ontario Hydro's SED initiatives, that of integrating SED into planning and decision making. Some key successes in this area since the Task Force report include:

— Approval for, and implementation of, an SED policy and principles;
— Progress in implementing full cost accounting (FCA);
— Development of decision tools, such as the SED decision criteria for investment decisions; and
— Use of FCA in a Corporate Integrated Resource Plan process.

3.1. SED policy and principles

Ontario Hydro's mission is "to make Ontario Hydro a leader in energy efficiency and sustainable development, and to provide its customers with safe and reliable energy services at competitive prices".

In April 1995, Ontario Hydro's Board of Directors approved an SED policy, guiding principles and strategic guidelines [2] that elaborate on Ontario Hydro's commitment to SD as expressed in the mission statement. This policy/principles/guidelines describe what SED means to Ontario Hydro and how SED will be implemented. This new focus on SED builds on many of Ontario Hydro's long-standing practices, for example:

— Identifying and managing the environmental impacts of its activities;
— Managing wastes and looking for opportunities to reduce/reuse/recycle;
— Working with communities in the neighbourhood of facilities to manage the impact of its activities;
— Promoting and practicing energy efficiency; and
— Auditing and reporting regularly on environmental performance.

Ontario Hydro adopts the definition of SD as "development which meets the needs of present generations without compromising the ability of future generations to meet their own needs" [3]. SED applies the principles of SD to the energy sector. A fundamental tenet of SED is the efficient use of energy, human, financial and natural resources.

For Ontario Hydro, SD is a strategy for achieving business success within environmental limits. Ontario Hydro acknowledges that SD is a long term goal, but believes that there are actions which can be taken now to ensure that the corporation is incrementally moving towards a sustainable energy future. Ontario Hydro's policy for SED states:

> "Ontario Hydro will apply the principles of sustainable development throughout its businesses. Ontario Hydro will increase its competitiveness and promote a more sustainable energy future by focusing, initially, on the efficient use of resources, continuous improvement in environmental performance, and diversification of its energy services and products."

This policy statement is elaborated in the following governing principles:

— Ontario Hydro will practice eco-efficiency, i.e. continuously add value to products and services, while constantly reducing energy use, material use, pollution and waste.
— Ontario Hydro will apply the 'precautionary principle' with respect to the human health risks and environmental damage resulting from its activities, and will take all cost effective measures, even where scientific consensus has not yet been established on the level of risk or damage.
— Ontario Hydro will integrate environmental and social factors into its planning, decision making and business practices.
— Ontario Hydro will participate in the development of public policy and programmes which promote SD, through business, Government, non-Government and educational initiatives.
— Ontario Hydro will work in partnership with stakeholders to promote business decisions and practices which will move towards SD.
— Ontario Hydro will educate, encourage and empower its employees to conduct their activities in an environmentally responsible and sustainable manner.
— Ontario Hydro will monitor progress towards achieving SD using measurable indicators and report regularly to all stakeholders.

The strategic guidelines indicate areas in which Ontario Hydro will seek opportunities to implement SED, in a pragmatic and incremental way.

3.2. Full cost accounting corporate guidelines

Consistent with the strategic guideline to integrate environmental factors into decision making, FCA corporate guidelines have been developed [4]. These are currently being discussed with external stakeholders such as the Government, customers, the financial community and environmental interest groups.

It is important to define FCA because there is a great deal of confusion over what FCA means. This can be partially attributed to confusion over definitions associated with 'full', 'cost' and 'accounting'. At Ontario Hydro, FCA is defined as a means by which environmental considerations can be integrated into business decisions. It is a tool which incorporates environmental and other internal costs, with data on the external impacts of Ontario Hydro's activities on the environment and on human health, and the respective costs and benefits. In cases where the external impacts cannot be monetized, qualitative evaluations are used.

Ontario Hydro's approach to FCA has two components (Figs 1 and 2):

— To better define and allocate its internal environmental costs, and
— To better define and cost the externalities associated with its activities.

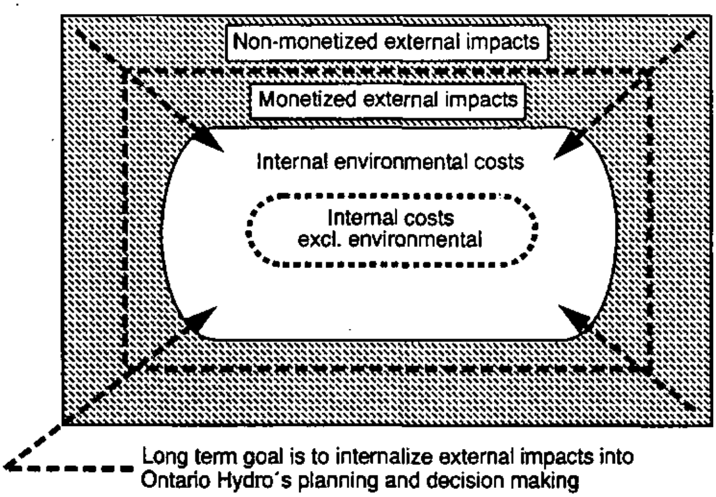

FIG. 1. Ontario Hydro's approach to full cost accounting.

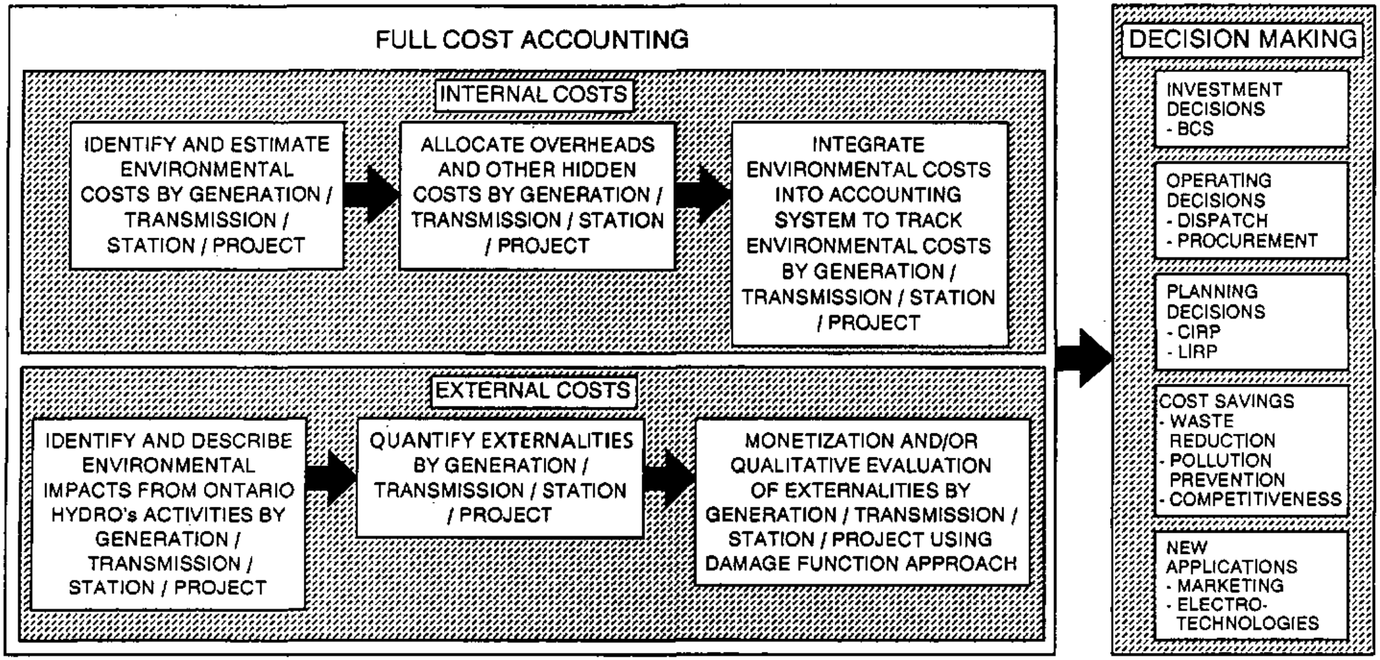

FIG. 2. Use of full cost accounting in decision making at Ontario Hydro.

The rationale for Ontario Hydro's support for FCA is severalfold:

— To improve environmental performance,
— To reduce operating costs,
— To provide a competitive advantage,
— To enable decisions to be made on the basis of least cost to society in Ontario,
— To assist in the transition towards a more sustainable energy future.

The production and delivery of electricity involves many operations and activities. There are many benefits associated with the production and consumption of electricity. These benefits are usually reflected in the price that consumers pay for electricity. In theory, consumers purchase electricity up to the point where its marginal costs (i.e. the price of electricity) just equal its marginal benefit. However, the price that consumers pay for electricity does not always include the full 'social cost' of producing and supplying that product. There are sometimes environmental and social impacts on third parties (i.e. individuals other than the producer or consumer) which are not explicitly taken into account by the party causing the effect — and hence are not included in product costing. These impacts are termed 'externalities'. Externalities can be positive or negative.

External impacts (externalities) are the impacts on human health and the environment (natural and socioeconomic) resulting from the production or use of a product/service which are not reflected in its cost or price. An external cost (benefit) represents the monetized value of an externality. An externality exists when the following two conditions are met:

— An activity by one agent causes a loss/gain of welfare to another agent, and
— The loss of welfare is uncompensated [5].

An example of an externality would be human health effects associated with air emissions from fossil fired electricity generation stations. An example of an externality that has been internalized would be compensation to a farmer for crop damages that could result from ozone.

It is important to note that what Ontario Hydro is trying to incorporate into the decision making process are the 'residual' impacts or, in other words, the environmental and social impacts that remain after all regulations have been met and mitigation and compensation have been undertaken.

Even after Ontario Hydro has met environmental regulations to control air emissions from its generating stations, there are still residual air emissions that can potentially cause damages to the environment and to human health. Ignoring these impacts and costs underestimates the environmental impacts of activities and the resulting costs to society and may result in inappropriate resource allocation decisions being made. Ontario Hydro believes that explicit consideration of these impacts and costs in decision making will lead to more sustainable decisions, improved environmental quality and lower societal costs.

Ontario Hydro supports the damage function approach to estimating the externalities associated with its activities. This approach considers:

— Site specific environmental and health data;
— How emissions/effluents are transported, dispersed or chemically transformed using environmental modelling techniques;
— How receptors (i.e. people, buildings, fish, forests) are affected by these emissions/effluents; and
— The monetary value of these physical impacts.

Monetized externality data have been established for the operation of Ontario Hydro's fossil fired stations located in southern Ontario and for the full life-cycle

TABLE I. EXTERNAL ENVIRONMENTAL COSTS (1992 ¢/kW·h) FOR FOSSIL FIRED STATIONS

Stations (units)	Externality costs[a]
Lakeview (1, 2, 5, 6)	1.66
Lambton (1, 2)	0.31
Lambton (3, 4)	0.13
Lennox	0.06
Nanticoke	0.46
Average	0.40

[a] Cost estimates include externalities associated only with the operation of fossil fired stations.

TABLE II. EXTERNAL ENVIRONMENTAL COSTS (1992 ¢/kW·h) FOR NUCLEAR STATIONS

Stations	Low	Nominal	High
Pickering A	0.005545	0.010001	0.119012
Pickering B	0.004298	0.007232	0.096800
Bruce A	0.001826	0.002198	0.006393
Bruce B	0.001549	0.001863	0.005503
Darlington	0.004604	0.006135	0.040101

of its nuclear stations (Tables I and II)[1]. These are preliminary estimates and, certainly in the case of fossil fired stations, the health impacts associated with the operation of these stations are underestimated. Monetized externality estimates have not yet been developed for Ontario Hydro's 69 hydroelectric stations or transmission or distribution line systems. Research is under way to identify these external impacts and costs and to develop comparable data for renewable energy technologies and for demand management initiatives.

Ontario Hydro has committed itself to use FCA to integrate environmental considerations into its planning and investment decisions. This will be done on a step-by-step, pragmatic basis. It is acknowledged that until a full range of externality impacts and cost data are developed, qualitative evaluations will be used where there are data limitations.

4. LINKS BETWEEN SED, FCA AND ENVIRONMENTAL ASSESSMENT

The link between environmental assessment and sustainable development is quite obvious. One of the principles of the Rio Declaration on Environment and Development, which was an outcome of the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, was that environmental impact assessment (EIA) shall be undertaken for proposed projects that are likely to have significant adverse impacts on the environment. EIAs are routinely undertaken in most of the developed world prior to project approval and are often one of the conditions of lending institutions for projects in the developing world. Banks are even asking for EIAs as part of due diligence requirements in support of loans.

The link between environmental assessment and FCA may not be as obvious upon first consideration. Methodologically there are parallels. Both consider the consequences of an action on the natural and social environment. FCA builds on environmental assessment and takes the analysis a little further by considering several additional factors:

— The environmental damages associated with the action. Using the example of a transmission line EIA, one could say that, typically, in considering the implications of clearing a right of way, and focusing on trees, the analysis would go only as far as to estimate the hectares of land that would need to be cleared, the types of trees that would be at risk and the number of trees that would be felled. In undertaking a damage based externality analysis, one would try to

[1] The externalities considered for the data in the tables are: health and environmental impacts associated with radiological emissions and fossil fuel emissions under the nuclear fuel cycle. The life-cycle boundaries are: upstream fuel, routine operations, accidents, decommissioning, low level wastes and used fuel.

go further and address the implications, for example, for the natural and aquatic ecosystems (species, etc.) that could occur as a result of cutting down the trees.

— Quantifying the environmental damage and, where possible, establishing a monetary value for the damage. This goes beyond prediction by considering the 'actual' environmental consequences of a similar action, by relying on other environmental research. For example, one would not only consider the acid gas emissions from a proposed coal fired generating station and the mitigation measures necessary to meet the acid gas regulation (i.e. scrubbers), but one would also consider the effects of the 'residual' acid gas emissions on crop damage, on lake acidification and on human health, and the costs involved.

FCA is also an effective tool in that it has the potential to translate environmental damages into quantities or dollars — terms that a planner or a decision maker can more effectively use when trade-offs are being made. While it is true that all environmental impacts cannot be monetized (for example, how can one assign a dollar value to ecosystem integrity or productivity?), FCA helps to make these environmental impacts more explicit so that decision makers are aware of the consequences of their choices.

5. EXAMPLES OF CASE STUDIES INTEGRATING ENVIRONMENT AND SED INTO PLANNING AND DECISION MAKING

Three examples of how Ontario Hydro is improving the way in which it integrates environmental considerations into its planning and decision making are provided. The first example relates to investment decisions, the second relates to how Ontario Hydro evaluates the environment in its integrated resource planning, and the third is an example of externality research efforts.

5.1. Investment decisions

Each investment proposal requiring senior management approval requires a business case analysis (BCA). One of the components of a BCA is a discussion of the 'SED implications' of the proposal. To ensure consistency in the analysis of the SED implications of investment decisions, SED Decision Criteria were developed. These were needed because a full range of monetized externality data are not available to effectively evaluate investment proposals. The Decision Criteria are consistent with Ontario Hydro's FCA approach.

These SED Decision Criteria focus on five components of an investment decision:

— Maximizing resource use and energy efficiency;
— Reducing environmental damage/impacts;
— Avoiding/improving social impacts;
— Increasing the use of renewable technologies; and
— Identifying financial gains attributable to SD initiatives.

The analysis of the environmental impacts of the preferred investment option and the alternatives should consider:

— The full life cycle, where possible, but, as a minimum requirement, impacts associated with the design, construction/production, operation/use, decommissioning and disposal;
— The expected damage to ecosystems, communities and human health; the analysis should not be based on the ability to meet existing or proposed environmental regulations;
— The identification and evaluation of the potential positive and negative environmental impacts of the alternatives, including impacts that are common among the alternatives;
— The quantification and monetization of the potential impacts, where possible, but, as a minimum requirement, a qualitative assessment of the impacts; and
— The trade-offs made in selecting the preferred alternative.

The role of the staff in the Environment and Sustainable Development Division is to provide advice on this assessment and to make an independent review of the SED implications of these business cases for the President and the Chief Executive Officer (CEO).

The SED Decision Criteria were implemented in September 1994 and eight BCAs were reviewed by the end of the year. All but one addressed the criteria appropriately and were recommended for senior management approval. One BCA was withdrawn, in part because of the environmental implications of the proposal.

In one case, a proposed investment decision for a Can$24 million transmission line refurbishment programme, the SED implications were:

— A 20% reduction in energy loss in transmission lines through the use of energy efficiency conductors;
— An annual increase in revenues of Can$ 5 million through reuse and recycling of removed line components;
— Initiation of a programme to improve the biodiversity of rights of way by restoring and replacing natural habitats; and
— Provision of employment and economic benefits to local communities.

This investment decision was approved and the programme is operational.

5.2. Environmental assessment for corporate integrated resource planning

The corporate integrated resource planning (CIRP) process was initiated in summer 1994 and was completed in summer 1995. The purpose of the CIRP was to provide strategic advice to the President and the CEO on resource allocation decisions for the 1996 business planning cycle. A range of demand side management and generation supply options were combined into seven plans and evaluated on the basis of their ability to fulfil the following objectives:

- To provide competitively priced energy services valued by customers;
- To improve environmental performance and make more efficient use of resources;
- To enhance social and economic benefits in Ontario; and
- To enhance the financial, operational and human resource viability of Ontario Hydro.

These objectives were used to develop the criteria by which the plans were assessed and evaluated.

One of the assessments was an environmental assessment. The environmental assessment was scoped to include the biophysical environment only; impacts on human health and the social environment were considered in separate assessments.

The primary criterion established for the environmental assessment was to minimize damages to the environment. The measures used were:

- Incremental land use (ha);
- Crop damage (Can$) resulting from ground-level ozone;
- Damage to the exterior of buildings (Can$) due to acid gas and particulate matter;
- Acidic deposition (mg/m^2) on sensitive watersheds;
- Waste generated (Gg by type of waste);
- Water flow modifications due to new hydroelectric developments (water flow ratio);
- Impacts of once-through cooling on littoral zones (index based on number, flow, capacity and mode of cooling water system);
- Greenhouse gas (GHG) emissions (Tg and Tg/TW·h);
- Radioactive waste in storage (Mg); and
- Consumption of non-renewable resources (i.e. coal, uranium, gas, limestone) (Mg).

The assessment was performed on an environmental damage basis, consistent with Ontario Hydro's FCA corporate guideline. Impacts were either quantified, and monetized where possible, or qualitatively described, depending on the data available. Additional SED considerations were included in the form of 'committed impacts', i.e. impacts that would result from the plans and would have to be managed by future generations (e.g. used nuclear fuel in storage; consumption of non-renewable resources; GHG emissions). Analysis was performed on a life-cycle basis.

Where applicable, environmental damages were assessed and mapped on a provincial watershed basis. Damages mapped were incremental land use, crop damage, damage to buildings and acidic deposition. Although the assessment team was not able to directly assess the impacts of the CIRP plans on the integrity of the watershed ecosystems, information was available on the current state of these systems. Ecosystem information used in the CIRP assessment included susceptibility to acidification based on lake buffering capacity, and vulnerability to additional land use pressures based on the degree of forest fragmentation as indicated by 'landscape conservation values'.

Multicriteria analysis (MCA) was used by the five-member environmental team to assist in making trade-offs among the eleven environmental measures in order to select the most important environmental indicators for evaluating the CIRP plans. The maps of the indicators of ecosystem vulnerability were used together with the maps of environmental damages to assist in this process.

Four key measures were selected; all are long term sustainability indicators:

- GHG emissions of the full fuel cycle because of the current corporate commitment to reduce GHG emission, potential impacts on future generations, and because impacts are not manageable with current technology;
- Incremental land use because of risk of habitat loss, degradation and fragmentation, corporate commitment to biodiversity, and little ecological redundancy in southern Ontario;
- Used nuclear fuel in storage because of its toxicity, the longevity of the problem and the potential effects on future generations; and because a technological solution is not yet available;
- Consumption of natural gas because it is a non-renewable resource in most limited supply and because there are inefficiencies in the combustion of gas to produce electricity.

These four measures were then combined with fourteen other measures (e.g. financial, socioeconomic, health risk) to evaluate the seven CIRP plans. MCA was again used to assign 'values' to the measures, to assist in making trade-offs in order to identify the most important components of the plans.

The environmental assessment for the CIRP represented an advance on similar assessments performed by Ontario Hydro in the past, in two areas, as detailed below.

First, the assessment was performed on an environmental damage basis. Some of the impacts were monetized; however, additional research is required in several impact areas to better quantify and eventually monetize impacts. For the next several years, until a larger number of impacts can be monetized, tools such as MCA will be necessary to compare the performance of plans relative to a broad range of impacts.

Second, some environmental damages were mapped on a watershed basis and compared with indicators of ecosystem vulnerability. Additional work is required to enable Ontario Hydro to better understand how its activities affect the integrity and productivity of ecosystems.

Further research is required in both of these areas to enable Ontario Hydro to continue to improve its ability to assess the environmental impacts of plans at the corporate level.

5.3. Study of grid externalities

Electricity produced by Ontario Hydro's generating stations is distributed to its customers through an integrated transmission network. The network consists of 30 000 km of high voltage transmission lines and 260 transformer stations. The lines are mostly above ground, at 115, 230 or 500 kV, and located on land either owned by Ontario Hydro or leased through easements. The transformer stations are on land owned by Ontario Hydro and include line termination structures, circuit breakers, high voltage transformers and capacitor banks. The Grid System Business Unit of Ontario Hydro plans, designs, acquires property and materials, builds, operates, maintains and decommissions the transmission facilities.

The life-cycle phases of these grid facilities include:

- planning and approval,
- acquisition of property and material,
- construction and commissioning,
- operations and maintenance,
- decommissioning.

In 1994, a Grid Externalities Team was established to undertake an examination of potential externalities associated with the activities connected with the transmission and distribution of electricity.

The initiative of the Grid Externalities Team is being conducted in three phases. Phase I and Phase II have been completed. Phase III will be initiated shortly. The following summary is an overview of work in progress. All of the information is still considered preliminary and is subject to change.

The mandate of the Grid Externalities Team in Phase I was:

- to identify potential grid related externalities; and
- to develop recommendations on how to proceed towards quantification and monetization of these externalities.

The team took the following steps in identifying grid externalities:

- It identified the life-cycle phases of grid facilities and activities and, in general terms, activities in each phase of the life-cycle.

— It identified potential human health, natural (including ecosystems) and social environmental effects for the above activities in each phase and categorized them into impact areas; the impact areas were terrestrial and aquatic ecosystems, socioeconomic effects, human health and visibility.
— It classified the environmental effects either as potential externalities or as internalized costs.
— It assigned to the potential externalities a high, medium or low priority.
— It identified relevant issues for examination.
— It developed a proposed scope of work for Phase II in 1994/1995.

The most significant potential grid related externalities identified by the team include:

— Impacts on human health (actual and perceived) from electromagnetic fields (EMFs) of transmission lines and transformer stations;
— Impacts on natural ecosystems along transmission corridors resulting from construction, operation and maintenance activities;
— Impacts on visual landscapes (perception of risk from EMFs and visibility impacts may overlap and be reflected in property values);
— Impacts on ecosystems and human health from herbicide usage, from accidents (fires and unplanned releases, e.g. polychlorinated biphenyls) and from disposal of decommissioned equipment and waste materials;
— Impacts on archaeological and cultural heritage sites from transmission facilities;
— Impacts on aboriginal communities from transmission facilities.

The team recommended that efforts should proceed towards quantification and, where possible, monetization of the potential externalities; identified in Phase I, through use of the damage function approach. The team also recommended that a case study be used to demonstrate how externalities could be assessed on an actual project.

The scope of Phase II was:

— to conduct literature reviews on potential externalities identified in Phase I; and
— to make recommendations on how to proceed towards quantification and monetization of grid related externalities.

A draft on Phase II is being prepared and Phase III work is scheduled to begin in the near future. The scope of Phase III is to quantify and monetize, where possible, potential grid externalities through use of a case study. The case studies being considered are vacant EIA studies of transmission line and transformer station projects that have been cancelled.

It is expected that the study of the Grid Externalities Team will be completed, to the extent possible, by the end of 1996. At that time, recommendations will be made on how to proceed to consider potential externalities that could not be quantified or monetized.

6. NEXT STEPS

As mentioned, SED is a long term goal for Ontario Hydro. 1994 and 1995 have been years for establishing the framework for SED and for accomplishing a number of small, but innovative, SED initiatives. Efforts to identify more effective mechanisms to integrate the environment into decision making will continue and work on FCA will proceed. The challenges for the next several years include:

— Improving the estimates of externalities, and their costs, associated with Ontario Hydro's fossil and nuclear stations, and expanding research to determine the externalities associated with hydroelectric stations and the transmission system;
— Demonstrating that practicing SED can improve competitiveness;
— Developing more widespread knowledge of, and support for, SED among employees through an aggressive communication and education programme;
— Developing an effective system to measure progress towards the achievement of SED (SD indicators are under development).

These challenges are significant and many groups are watching our progress. We are confident that SED is the right path and that we will be successful.

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ELECTRICITY AND POLICY IN SOUTH AFRICA AFFECTING ENERGY DEMAND AND SUPPLY

R.K. DUTKIEWICZ
Energy Research Institute,
University of Cape Town,
Plumstead, South Africa

Abstract

ELECTRICITY AND POLICY IN SOUTH AFRICA AFFECTING ENERGY DEMAND AND SUPPLY.

South Africa is facing a fresh challenge regarding the formulation of its policy in the field of energy and especially electricity. At present, the Government is preoccupied with a Reconstruction and Development Programme (RDP) which seeks to redress the social inequalities of the past. One important thrust of the RDP is the supply of electricity to the approximately two thirds of the population who are not connected to the grid system. This is likely to overshadow the need for a reappraisal of the methods of decision making in the electricity supply sector and the need to carry out adequate comparative risk assessment studies. For a developing country such as South Africa it is important to evaluate the externality costs of electricity generation in order to minimize the cost of electricity on a national basis. In the past, electricity generation came predominantly from coal fired power plants, with nuclear power providing some 6% of the installed capacity. In future, there will be an increased number of options, since gas and hydropower will be available from imports. Hydropower is available from South Africa's immediate neighbours, but the largest part is from the Zaire River, which has a potential of over 80 000 MW, 40 000 MW of which is from a run-of-river plant situated on a short section of the Zaire River at Inga. These alternatives as well as the use of nuclear and clean-coal technologies could make it possible to significantly reduce the environmental impacts of electricity generation. Assistance from developing countries in which these technologies have been successfully applied will be necessary for South Africa to adequately implement a programme of comparative impact assessment and externality evaluation.

1. INTRODUCTION

Worldwide planning for electricity generation, transmission and use has moved from a technological approach through an environmental approach to the present integrated or holistic approach. These moves were initially made because of the growing pressure from environmental groups. Later, it was realized that the costs of externalities must be incorporated into the total cost of electricity in order to optimize the benefits to the community or the country. This applies to all energy forms, but this paper addresses the electricity sector and, more specifically, the electricity sector in a developing country such as South Africa.

South Africa is often included in the list of developed countries because of its wealth and its infrastructure. Whilst it is true that South Africa has some of the characteristics of a developed country, its proper place is in the group of developing countries, because of its low gross domestic product (GDP) (US $2500 per capita), its high ratio of poor people to wealthy people, its overall social underdevelopment, and the little attention being paid to the state of its environment.

Developing countries require economic growth in order to attain an acceptable standard of living for their people. An efficient economic system is therefore possibly more important for developing countries than for developed countries, which can afford the luxury of carrying out certain projects for aesthetic reasons or for the purpose of gaining public acceptance of environmental measures. In order to achieve overall maximum financial efficiency for the whole country, internalization of externality costs is as important in developing countries as in the developed world. However, the very backwardness of the financial systems and of the infrastructure in these countries makes the quantification of these externality costs very difficult. It is, however, important to make at least some quantification and to consider decisions on increases in generation, transmission and distribution capacities in a holistic fashion.

In South Africa, economic growth and development are regarded as essential priorities, and social improvement is an important national goal. This involves improvements in housing, better access to water, improved health services, greatly improved education, and access to electricity for the 60% of the people who currently do not have such access. The social improvement programme was therefore given priority when the reconstruction and development programme (RDP) was set up by the Government under a Cabinet Minister.

Going together with this emphasis on social improvement is a growing concern about the state of the environment. However, the provision of funds for improving or defending the environment is often in direct conflict with the aims of the RDP.

It is against this background that the concept of comparative assessment is becoming increasingly important, even though formal measures for carrying out such assessments are not yet in place nor are they fully understood. However, recent public objections to a number of large engineering projects, including a mining operation in sand dunes and construction of a new steel works near a national heritage site, resulted in demands for improved environmental impact studies before granting permission to proceed with such projects. So far, such impact studies were carried out on independent projects, without much consideration of comparative studies of a number of alternatives. The situation is usually characterized by the 'Nimby' (not in my back-yard) concept. However, this situation is changing in favour of a proactive approach to integrated planning.

2. THE ENVIRONMENTAL MANAGEMENT FRAMEWORK

Concern over the environmental impact of some large industrial projects has led the Government's Department of Environmental Affairs to prepare an integrated environmental management guideline. This guideline recognizes that economic development is an important national goal and that therefore the aim is not the achievement of a zero environmental impact but rather the control of impacts, depending on the particular circumstances of each case. The guideline requires an analysis of the life cycle of a proposed project, including the following components:

- Formulation of the proposed actions required to meet a certain need, and evaluation of the environmental effects of the proposed project and of one or more alternative proposals to meet the same need.
- Identifying, obtaining approval and setting conditions for the action that serves best the overall interests of society.
- Successful implementation and management of the project during its lifetime, bearing in mind that management has to be implemented as a flexible process.

The integrated environmental management plan therefore recognizes the beneficial aspects of development and gives directives for optimizing actions in order to achieve the best results for society. This plan has been adopted by ESKOM — the main electricity producer in South Africa.

3. THE ELECTRICITY INDUSTRY IN SOUTH AFRICA

The main actor in the South African electricity industry is the parastatal utility ESKOM, which produces some 97% of the total electricity supply. It carries out bulk transmission and distributes electricity to certain consumers and areas; there are, however, a large number of other distributors, including the larger municipalities.

Until recently, the distribution of electricity was subject to a licence issued by the Electricity Board. This board was replaced by the National Electricity Regulator, which was given large powers, covering the generation, transmission and distribution of electricity. However, the Regulator was not specifically charged with evaluating the impact of electricity production. The emphasis is currently on the contribution of electricity to the RDP, on the aspects of payment for services in underdeveloped areas in connection with achieving the electrification goals, and on whether municipalities should be allowed to cross-link electricity tariffs to the cost of other municipal services. Sight has been lost of the fact that residential electricity consumption only accounts for 15% of the total electricity consumption and that electricity planning and pricing have a significant effect on the economic growth of the country through its impact on the industry.

Unlike many developing countries, South Africa has a surplus of generating capacity; this was caused by a high forecast of the growth rate for the 1980s, which did not materialize because of the down-turn in the world economy and because of the effect of sanctions on South Africa. The problem in the short to medium term (say the next ten years) will be to increase electricity consumption in order to decrease the unit price of electricity. However, in order to achieve economic growth, planning for the next tranche of generating capacity needs to start immediately. In the medium term, reliance will continue to be placed mainly on coal fired power plants, with a smaller contribution of gas fired plants based on imported gas from Mozambique and Namibia. In the longer term, it will be possible to import hydropower from surrounding countries, such as Namibia, Mozambique and Zimbabwe, and at a later stage also from countries in Central Africa rich in hydropower, especially from Zaire, which has a potential of around 80 000 MW of hydro capacity. In the long term, nuclear generation will also become attractive, both because plants can be located on coasts and require no inland water and because nuclear is a source of diversified power.

Most of South Africa's electricity generation is based on coal fired plants in the eastern Highveld, with some 24 000 MW of installed coal fired capacity in an area of around 200 km by 200 km. Because of this density of power generation there has been concern that the combined effect of these power stations could lead to serious acid rain conditions downwind of the region; at present, there is a moratorium on further expansion of generation in this region. ESKOM has carried out extensive monitoring in this region and downwind of it and the time has come to perform a detailed analysis of the situation and of the potential future problems.

At present, there is no overall integrated policy on electricity generation that could include aspects of environmental impact control. An operating permit from the Government's chief air pollution officer is required for each power station to be built. This permit is issued bearing in mind the best practicable methods of operation, including emission control technology, and the particular site of the plant. Because of the predominance of coal fired plants in the eastern Transvaal (now Mpumalanga) a temporary ban was placed on new power plant construction in this area in order to limit SO_2 emissions from power plants in this region until a comprehensive study of the potential for acid rain formation in the region is conducted and the effect of SO_2 ground level concentrations can be assessed. In view of the low sulphur content of South African coal, typically 0.9%, it was not deemed necessary to specify any de-SO_x equipment for power stations. In view of the lack of evidence of acid rain, no de-NO_x requirements are thought to be necessary.

3.1. Electrification

Electrification refers to the provision of electricity to a large proportion of the two thirds of the people who are not connected to the national grid. The driving force behind electrification is social improvement and the correction of the historical bias in the South African society. It will, however, be necessary to meet the environmental challenge posed by the large electrification programme in a responsible manner, by trying to avoid the errors made in developed countries and in eastern Europe. Some of South Africa's most serious environmental problems are associated with its pattern of energy use. The main problems are those associated with the over-exploitation of fuelwood, and the use of coal for cooking and heating by people living in the poorer sections of the Highveld region around Johannesburg.

It was considered that many of the problems associated with the use of coal in the Highveld region could be alleviated by the provision of the townships with electricity. An electrification programme was enthusiastically adopted, but the initial impact on the environment was limited. One of the reasons for the poor results was the fact that the start of the programme coincided with a period of political change in South Africa, which culminated in the development of a new democracy. However, in the course of the process, political pressure on the previous Government included the adoption of a non-payment strategy for services, including electricity, and the cut-off of electricity supplies. A more long term problem is connected with the fact that, even in those cases where electricity was provided to underdeveloped areas, it was used mainly for lighting, radio and television sets, while coal was still used for cooking and heating. The reasons for this are manyfold, the main problem being the high cost of electricity compared with the cost of coal. There was also a cultural perception that coal was a better source of heat than electricity.

It is now apparent that it was over-simplistic to consider that electrification would lead to a large reduction of air pollution, and attempts are being made to reduce the air pollution in townships by a multi-pronged attack that includes electrification and the use of smoke-free fuels and stoves.

3.2. Nuclear power

South Africa is the only country on the African continent which has a commercial nuclear energy programme. The Koeberg nuclear power station, situated 30 km north of Cape Town, has an installed capacity of 1840 MW. Legislative safety control of the plant is the responsibility of the Council for Nuclear Safety (CNS) — a nuclear regulatory authority set up by an act of Parliament in 1973. The function of the CNS is to regulate all activities in South Africa involving the use of radioactive material and posing a significant risk to the public or the plant personnel. This includes most aspects of the nuclear fuel cycle and the operation of the Koeberg power station.

It is a statutory requirement that the operator of a nuclear power station submits, and updates on a regular basis, a public risk assessment in order to demonstrate compliance with the limits set by the CNS. Over the past fifteen years, risk assessment studies have been developed for virtually all aspects of the nuclear fuel cycle, including a research reactor, enrichment plants, a waste repository and certain aspects of mining operations. As regards the Koeberg nuclear power station, the source terms include: power and shutdown modes, spent fuel storage, fuel handling accidents, and accidents in connection with waste treatment. The present fundamental safety standards include risks to the public and the plant personnel from normal operation and accidental releases, as well as limits on maximum and average individual risk. For societal risk a bias against large accidents has been imposed.

4, COMPARATIVE RISK ASSESSMENT

Studies of environmental impacts of electricity generation in South Africa were carried out on the basis of a single power station using coal; no comparative studies were made. The reasons for this were the reliance on one fuel source for electricity generation, namely coal, and the concentration of the coal mines in one area. The situation is changing, for three main reasons:

(1) As a consequence of South Africa having entered the political arena of the continent, there has been a number of regionally based electricity generation options. Thus, hydropower will become available from surrounding countries, such as Namibia, Mozambique, Zimbabwe and Zambia. In addition, there is a possibility of generating electricity using gas imported from Namibia and Mozambique. The technical aspects of the transmission of large blocks of power over long distances are no longer obstacles to such schemes and the growing political stability in the region makes it possible to consider such projects.

(2) Coal for power generation was once obtained from a single area in the eastern Transvaal, but more sites are now available for positioning of power stations on other coal fields. This was made possible by the discovery of new coal fields and also by the development of a technology that allows power stations to be positioned in areas where water is in short supply, for instance by using dry cooling.

(3) Because of the worldwide concern about global warming, it will be necessary for South Africa to consider alternative electricity production methods that have a lower impact on the environment in terms of releases of gases implicated in global warming, such as carbon dioxide. Thus, the use of gas and hydropower will become more attractive and it will be desirable to adopt improved coal utilization techniques such as combined cycle coal gasification.

Thus there are now more energy generation options and there is an increased awareness of potential environmental damage, which makes a more systematic assessment of the alternatives important. The Integrated Impact Assessment approach, which is being adopted by the Government, is a first step in realizing a comparative risk assessment. However, full implementation of a comparative study has to include an evaluation of the financial burden in connection with solving environmental problems; it becomes imperative to quantify externality costs, at least some of them.

One of the significant unknowns in the determination of externality costs is that of global warming. This is complicated by the basic question of how much of the problem of global warming is the responsibility of the developed world and how much of the solution of the problem can be imposed on developing nations. In the case of South Africa (and China, India, etc.), which has cheap coal and a high energy cost as a fraction of the GDP, the inclusion of an externality cost for global warming could well double the cost of electricity and increase inflation by some 20% — an untenable situation, bearing in mind the needs of reconstructing the economy and improving the standard of living of a large percentage of the population.

A serious problem in the evaluation of externality costs is the lack of information on the technical environmental impact of electricity generation. A first estimate was made of the costs of mortality and morbidity due to the complete fuel cycles associated with the generation of electricity from coal fired power stations, from nuclear power stations and from solar and wind energy. The analysis was difficult because there was no information on the impact of power generation on the flora and fauna in South Africa, and no discussion of subjective issues such as aesthetics and diversity of species. Therefore, the analysis dealt mainly with the morbidity and mortality of the people involved in the whole fuel cycle, from mining to electricity supply.

5. THE FUTURE OF THE ELECTRIC INDUSTRY

In view of the present political climate in South Africa, the electrical utility ESKOM will remain a parastatal and there will be pressure to operate it as part of the RDP. One of the key factors in this situation will be the emphasis on providing electricity to the whole population. The cost of this will have to be borne by the utility, even for areas where capital expenditure cannot be recovered. This will mean cross-subsidies of the residential sector by the industrial sector, and tariffs will increase in order to satisfy the increased expenditure.

In spite of the increase in demand due to the electrification programme, there is sufficient surplus capacity to satisfy the demand until about 2005. There are a number of options for new generating plants. The first option is to continue operation of coal fired plants, using units of about 900 MW capacity and traditional pulverized fuel technology. This option is fairly well understood and is known to have a very low cost of electricity.

One alternative to the tried and tested route is to adopt a more environmentally acceptable attitude and to move to clean coal technology, including the use of the combined cycle coal gasification technology. This technology is not yet commercially available, and ESKOM will not be prepared to build and rely on large units of this type; however, the company may well build a small unit to obtain experience in the utilization of South African coal for this technology.

A third alternative is to use gas from Namibia and Mozambique in a combined cycle plant. This is an attractive proposition if the cost of gas can be brought down to the equivalent cost of coal used in pulverized fuel boilers. Environmentally this has advantages over coal combustion.

The fourth alternative is to import hydro based electricity from surrounding countries, such as Namibia and Angola, from countries in the Zambezi Valley and from Zaire. Except for Zaire, the hydro potential in these countries is relatively small and could only meet a limited part of the new demand. The hydro potential of Zaire is large — 40 000 MW from plants situated on a short section of the Zaire River at Inga, and a further 40 000 MW from plants located on the remainder of the river. The cost of the hydropower plant at Inga is relatively high compared with the cost of a coal fired plant near the load centre. This will change with time as the potential import capacity grows, and this option will become attractive when the export capacity exceeds 10 000 MW.

The fifth alternative is the use of nuclear power. Nuclear power is attractive in South Africa because water is scarce, and nuclear power stations can be positioned at the coast and the electricity can be transmitted to inland centres of high demand. At present and in the medium term, nuclear power is likely to be more expensive than coal, with a cost of US $0.8/GJ. However, coal will become more scarce in the next century and it is estimated that the last coal fired power station will be commissioned about the year 2020. The prospects for nuclear power in the long term are good, with regard to both resources and the increasing pressure to protect the environment.

5.1. Future electricity choices and environmental impacts

While the levels of SO_2 and acid rain deposition in the eastern Transvaal are not seen as giving grounds for concern at present, it is likely that there will be increasing pressure on ESCOM to adopt more advanced systems of emission control. These will include de-SO_x and advanced equipment for the control of particulate matter. The base cost of alternative generating systems will be the deciding factor, but there is a growing awareness of the fact that externality costs should be internalized, where possible. There is also international concern because South Africa emits very large quantities of CO_2. The reason for the relatively high emission of CO_2 is the rather high energy intensity of the economy and the reliance on coal for energy production. However, there will be international pressure on South Africa to reduce its CO_2 emissions and electricity generation will have to conform to this requirement. Therefore, the move from conventional pulverized coal power plants to plants with a more environmentally acceptable clean coal technology may take place earlier than would be dictated by generation economics. It is also possible that, for environmental reasons, the move to additional imports of gas and hydropower might come earlier than is economically desirable.

5.2. Policy issues

In the past, there was no significant policy mechanism for electricity because of the fact that ESKOM operated efficiently with regard to the perceived goal of minimal cost for the industrial use of electricity. With the move towards a new democracy, there will likely be increased policy pressures for the utility to implement the RDP. This may be at odds with the desirable policy of ensuring that consumers pay the full costs of the energy resources they consume.

The desirable policy structure for the operation of ESKOM can be summarized as follows: The electrical utility should:

- Ensure that customers pay the full cost of the energy resources that they use; where applicable, this should include externality costs.
- Evaluate the full impact of electricity production on the environment.
- Operate according to the Government's international agreements and commitments on environmental matters.
- Safeguard the health and safety of its employees and of the population.
- Promote the efficient utilization of electricity.

In order for this to be achieved, the Government must ensure the existence of a satisfactory and stable legal and regulatory framework within which markets can operate. In addition, the Government should not interfere with the normal market force operation of the utility. If any form of subsidising of tariffs is necessary for social reasons, the Government should take care of this; the reason for the subsidy should be transparent and the amounts involved publicly documented. It should not be required for a utility to use internal cross-subsidies.

6. CONCLUSIONS

South Africa is going through a process of policy analysis and formulation in the framework of its new democracy, in all areas of the economy, including energy and the environment. Attempts are being made to achieve the highest degree of transparency and participation. However, the technical and economic complexity of the energy scene makes an adequate debate of energy issues difficult. The result of this debate will hopefully be a market oriented energy sector with minimum interference from the Government. It is, however, the task of the Government to set the environmental policy and structure within which the market forces can operate.

In line with other developing countries, South Africa was not able to develop adequate methods for comparative risk analysis and for the quantification of externality costs. This is an area where the developed countries can assist the less developed countries.

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CLIMATE CHANGE MITIGATION STRATEGIES IN GERMANY
Findings from the IKARUS project

D. MARTINSEN, W. KUCKSHINRICHS,
P. MARKEWITZ, J.-F. HAKE
Forschungszentrum Jülich GmbH,
Jülich, Germany

Abstract

CLIMATE CHANGE MITIGATION STRATEGIES IN GERMANY: FINDINGS FROM THE IKARUS PROJECT.

In the framework of the German IKARUS project, a bottom-up energy model and a dynamic macroeconomic input-output model have been developed. First model runs have been carried out for the region of the former German Democratic Republic, under the restriction to reduce the energy related CO_2 emissions by 25% by the year 2005 compared with the CO_2 emissions in 1989.

1. INTRODUCTION

In 1990, the Federal Government pledged itself to reduce the CO_2 emissions in Germany by 25–30% by the year 2005 compared with the CO_2 emissions in 1989. This reduction target is valid for the whole country. Furthermore, the commission for the study on Preventive Measures to Protect the Earth's Atmosphere, which was initiated by the German Parliament, recommended a CO_2 reduction of 50% by the year 2020. On the basis of the work of the commission, the Federal Ministry of Education, Science, Research and Technology initiated the IKARUS (instruments for greenhouse gas reduction strategies) project in 1990. The aim of the project is to provide tools for developing strategies to reduce energy related emissions of greenhouse gases in Germany. A range of instruments are being developed, consisting of models, a database and various tools. With the aid of alternative action sequences to reduce greenhouse gas emissions, scenarios for the period up to the year 2020 can be simulated and evaluated [1]. First applications are presented below.

2. MODEL DESCRIPTION

The model IKARUS-LP gives a static representation of the linearized energy system of Germany (Fig. 1) for the reference years 1989, 2005 and 2020. It covers the energy flow from the primary energy sector to the energy end-use sectors, i.e.

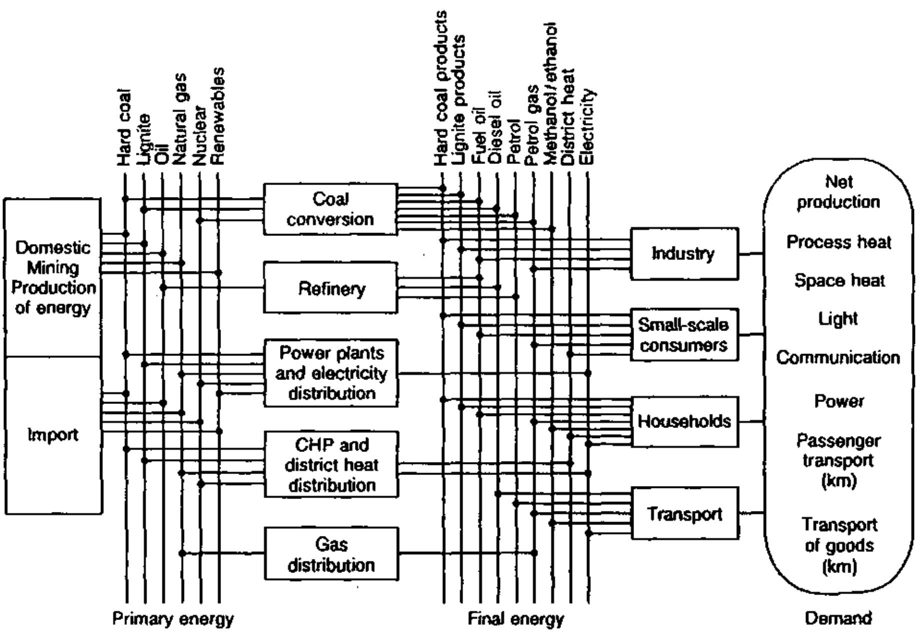

FIG. 1. Structure of the energy system model.

the industry, transport, households and small scale consumers. Links between energy sources, conversion and transport of energy, and energy sinks are indicated in the figure.

The primary energy sources, described by techniques, are subdivided into non-renewable and renewable energy carriers, comprising fossil fuels, nuclear energy, hydropower, wind energy, biomass, solar energy and geothermal energy.

Conversion and transport losses arise during the whole process, from the provision of primary energy to the fulfilment of the demand for useful energy. Linkages between the energy flows are achieved by the techniques used, which are described by specific inputs per unit outputs. Cost and emission flows are modelled simultaneously.

To fulfil the exogenously determined energy demand, the model offers a solution for system cost minimization for the energy supply. This includes the optimal energy technology structure and the optimal energy carrier mix. Restrictions, e.g. the maximum permissible CO_2 emissions, must be determined exogenously.

The LP model is linked to a macroeconomic model (MIS). The heart of MIS is a demand driven, dynamic input–output model (IO model) with 24 sectors, including nine energy sectors. The aggregation of the energy sectors deviates from that given in official national production statistics in order to improve modelling of the energy flows and their interlinkages. Because of their particular significance with regard to CO_2 reduction, the space heat and private transport sectors are introduced as artificial production sectors.

The two models are linked by implementing technical parameters, resulting from an optimization run of IKARUS-LP, in the macroeconomic model. These technical parameters comprise, for example, energy flows, such as the use of domestic hard coal and nuclear energy, and the capital structure in the production sectors.

In addition to the calculations for the energy optimization model, the macroeconomic model calculates not only the direct investment costs induced in the energy sector by the reduction of CO_2 but also the indirect effects in the sectors producing the investment goods for the energy sector. The results of the following new calculation with the macroeconomic model have to be compared with the basic assumptions as well as with the results of the preceding run of the energy optimization model. It is expected that an iterative process will have to be applied in order to obtain comparable solutions.

3. BASIC ASSUMPTIONS

The calculations concentrate on the years 1989 and 2005 for the region of the former German Democratic Republic. (An extension of the model database to include data for 2020 and for the 'new German countries' is being prepared.) The basic assumptions comprise economic and demographic developments and energy related political decisions. These include the expected development of macroeconomic variables such as the gross domestic product (GDP) and the prices of imported energy, the resulting determinants of energy demand, as well as political decisions and measures restricting the use of primary energy carriers and conversion techniques (Fig. 2).

On the basis of the predicted economic development (e.g. by PROGNOS), as well as a detailed sectoral analysis and our own estimations, AGEP and STE expect the GDP to increase in real terms from 2071×10^9 DM (1989) by the year 1989 to 3572×10^9 DM (1989) by the year 2005 (Fig. 1). The prices of imported energy carriers develop in different ways: for hard coal the price is stable; crude oil increases at a smooth rate of 1%/a and natural gas increases at a somewhat higher rate of 1.5%/a; additional natural gas imports (above 2000 PJ/a) are 25% more expensive. The population will remain nearly constant between 1989 and 2005, though there is a peak at the end of the millenium. Demographic effects result in a smooth increase in labour supply to about 30.3 million people.

The development of the economic and demographic variables results in new determinants of energy demand by the year 2005 (Fig. 2). The process heat demand of the industry is expressed as net production. It will increase to 904×10^9 DM

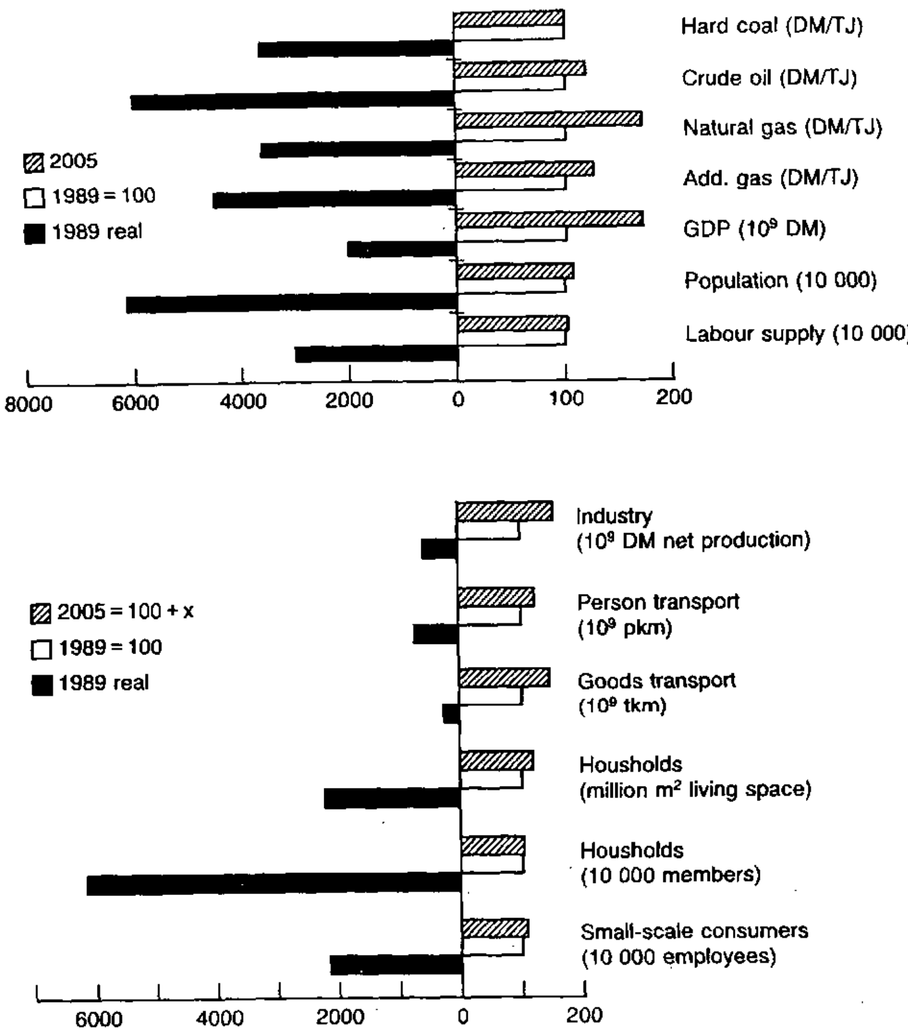

FIG. 2. Basic assumptions and determinants of energy demand.

(1989) by 2005. The energy demand for transport is divided into the demand for person-kilometres (pkm) and tonne-kilometres (tkm) and will increase to 899×10^9 pkm and 415×10^9 tkm by 2005. The energy demand for households depends on the demand for process heat, hot water and light/communication (all measured in terms of household members); the demand for space heat is measured according to the living space. The living space will increase to 2586 million m^2, whereas the number of household members will amount to 64.2 million by the year 2005. Analogously, the energy demand of small scale consumers is divided into the same categories, but measured in terms of employees, which will increase to 23.5 million.

Because of the energy policy and the country specific energy market structures in Germany, several assumptions have to be formulated to specify the technical options for the year 2005. The main assumptions for 2005 are:

(a) A lower limit of 900 PJ on the use of domestic hard coal for electricity production and steel production;
(b) A lower limit on the use of domestic lignite for electricity production;
(c) An upper limit on the import of cheap hard coal (800 PJ);
(d) The imports of natural gas and oil are grouped by increasing import prices;
(e) The nuclear capacity of power stations is not allowed to increase;
(f) Upper limits on the construction of new, enhanced utilities based on hard coal, lignite and gas of the order of 10 GW for each type;
(g) Several specific limits on dynamics in the end-use sectors concerning the substitution of energy carriers and technological changes (these limits are due to the short time period up to 2005); for example:
  - upper limits on industrial efficiency gains;
  - upper limits on changes in modal split, i.e. shifts from individual transportation to public transportation;
  - upper and lower limits on changes in heating systems and energy savings for households and small scale consumers according to building stocks and building standards as well as governmental measures.

These restrictions reflect a range of predictions made for the coming ten years.

4. RESULTS

To describe the effects of an energy related CO_2 restriction on the structure of the energy supply and energy saving techniques, as well as on the overall economy, the following cases are considered:

(a) **Base case (Base)**
The base case corresponds to the situation in 1989, based on the structure of the energy optimization model.

(b) **Business as usual (BaU)**
This is the reference case for the year 2005, which is based on a 'business as usual' scenario. This means that no specific measures to reduce CO_2 emissions are taken. However, as a result of structural effects in the production sector and technical progress implemented via ordinary investment measures, the energy related specific emissions may decrease.

(c) **Reduction case (Red)**
The CO_2 reduction case for the year 2005 is based on the reference case (BaU), but it includes a restriction of CO_2 emissions corresponding to a reduction of 25% compared with the 1989 value.

The base case represents the starting point for the calculations. To figure out the effects of a reduction of CO_2 emissions, the business as usual case and the reduction case have to be compared.

Figure 3 shows the results of the calculations for the primary energy demand. The total amount of primary energy does not change significantly from 1989 to 2005 (BaU), despite an increase in demand in all sectors. This is mainly due to an increase in conversion efficiency (electricity and process heat facilities) and to structural changes in the end-use sectors. A restriction of CO_2 emissions by 25% reduces the primary energy consumption by approximately 10%.

There is, however, a shift of the energy carriers from coal and oil to natural gas (plus 44%). The lower limit for domestic coal is not exceeded, whereas cheap hard coal is imported. An increased use of natural gas takes place in all sectors; for example, the production of electricity from gas based utilities more than doubles.

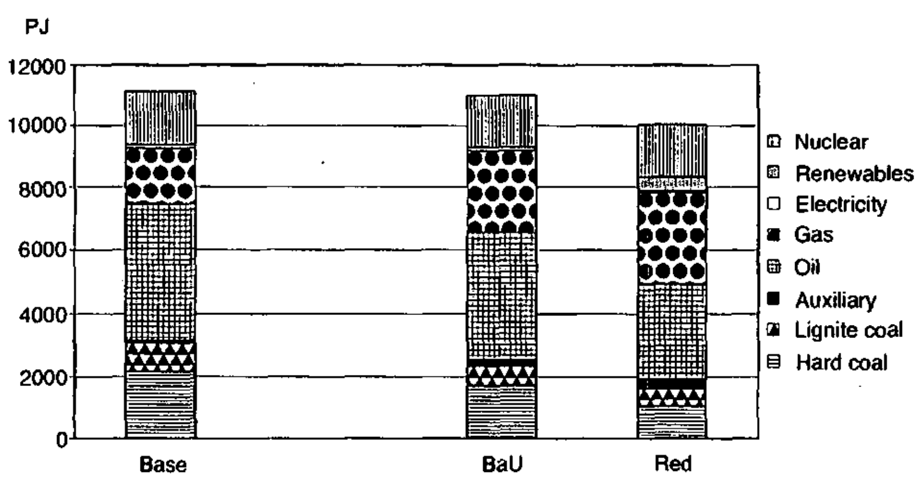

FIG. 3. Results of the calculations for primary energy demand.

The share of natural gas in 1989 is about 16%; it increases to 24% in the reference case (BaU) and to nearly 27% in the reduction case. Parameter runs, which are not described in this paper, have shown that the share of natural gas reaches a peak (30%) in the case of a CO_2 reduction by 15%. An additional increase in the CO_2 constraint results in a decrease of the natural gas share because of different price categories for gas. In this case, energy saving measures, such as the use of renewables for electricity production and cogeneration, are more cost effective.

In the reduction case, the input of natural gas for conversion is about 28% of the whole gas consumption and is used for electricity and district heat production. The main part of natural gas (72%) is consumed by the end-use sectors, especially the residence sector. The share of the residence sector of the whole natural gas consumption rises from 33% (605 PJ) in 1989 to 40% (1175 PJ) in 2005 for the reduction case.

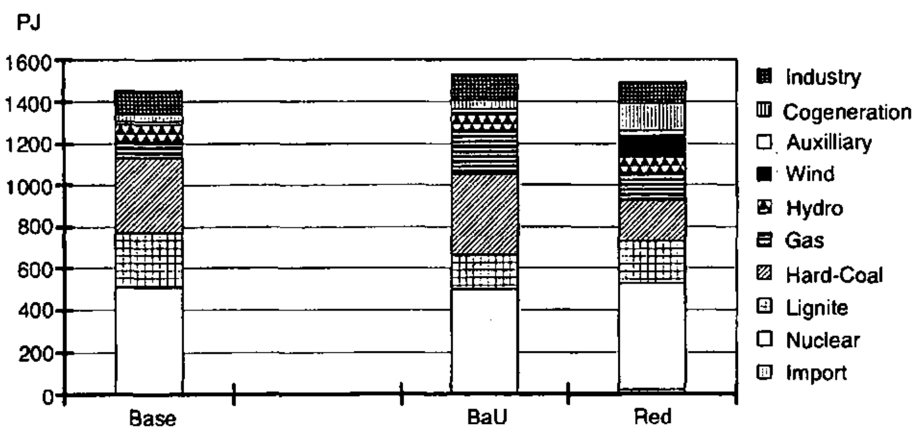

FIG. 4. Results of the calculations for electricity production.

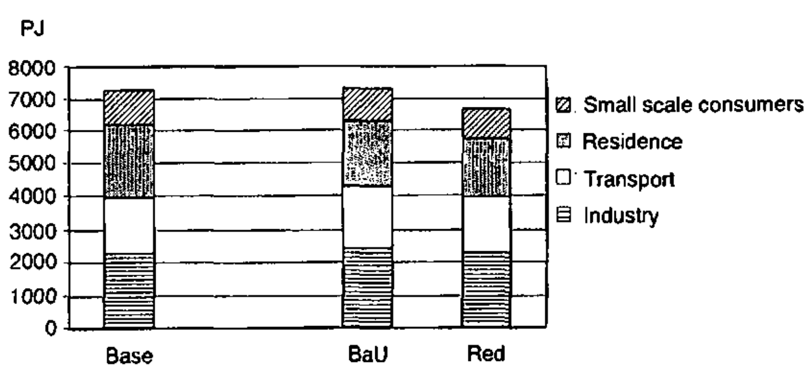

FIG. 5. Share of sectors in the final energy demand.

Electricity consumption increases only slightly in the reference case. In the other cases, the CO_2 emissions from electricity production decrease by 37%. However, as mentioned above, there is an increase in gas utilities and a decrease of utilities based on lignite. In the reduction case, more electricity is produced from cogeneration (biomass and biogas) and wind converters, whereas coal based electricity production decreases (Fig. 4).

Figure 5 shows the share of the different sectors in the final energy demand. The absolute value of final energy consumption for the reference case is equal to that of the base case and decreases by 8% for the reduction case. In all sectors there is a gain in energy efficiency, which partly compensates the increase in demand. In the residence sector and the small scale consumer sector, additional measures to reduce space heat demand, such as insulation of buildings, as well as a more effective use of electricity lead to a decrease of final energy demand compared with that for 1989 for the reference case and the reduction case. The final energy demand for the industry sector and the transport sector increases by 6% and 13%, respectively, in the reference case. Energy saving measures in these sectors do not compensate the increase in demand. Compared with the reference case the final energy consumption of the industry sector and the transport sector declines by 12% and 4%, respectively, in the reduction case. The absolute values are equal to those in the base case.

Model runs have been carried out for the reduction case without an additional constraint on nuclear energy. For this scenario, the primary energy consumption decreases by nearly 13% compared with that in the base case. The final energy demand decreases by 20% compared with that in the base case and by 12% compared with that in the reduction case. The decrease is mainly due to energy saving in the residence sector.

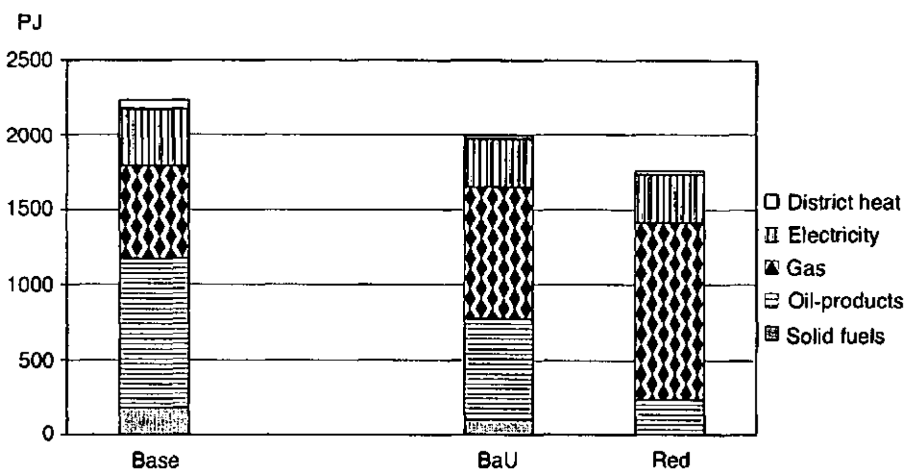

FIG. 6. Final energy demand in the residence sector.

Figure 6 illustrates the amount of energy saving and the change of energy carriers in the residence sector. In the reduction case, the final energy demand in 2005 is about 20% less than that in 1989, and the share of natural gas is strongly increased (2/3 of the total final energy in the reduction case).

The structural change of private transport from 1989 to 2005 is shown in Fig. 7. Although the share of public transportation is growing (from 18% to 22%), individual passenger transportation increases (by 17%) compared with that in 1989. In the reduction case, conventional motor-cars are replaced by ones with low fuel consumption in order to meet the CO_2 emission limit.

Figure 8 summarizes the results by allocating all CO_2 emissions to the different sectors. It is remarkable that there is a decrease of CO_2 emissions (minus 6%) over the period 1989–2005 also in the reference case. This can be explained by the

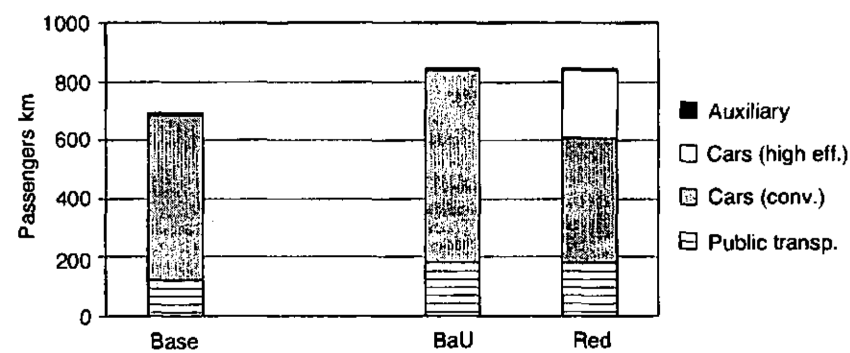

FIG. 7. Structural change of passenger transport.

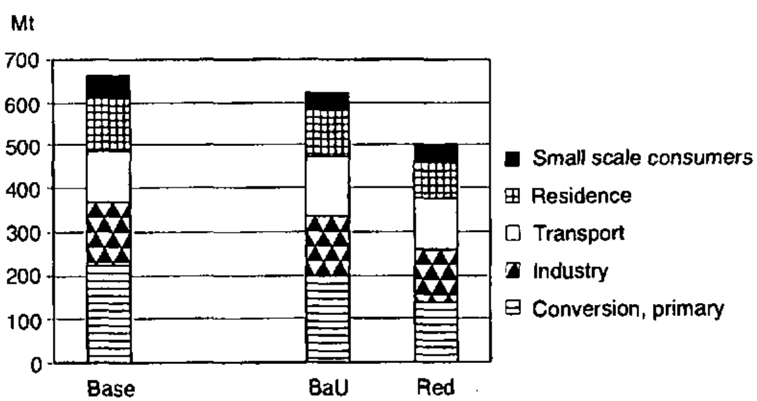

FIG. 8. CO_2 emissions from all sectors.

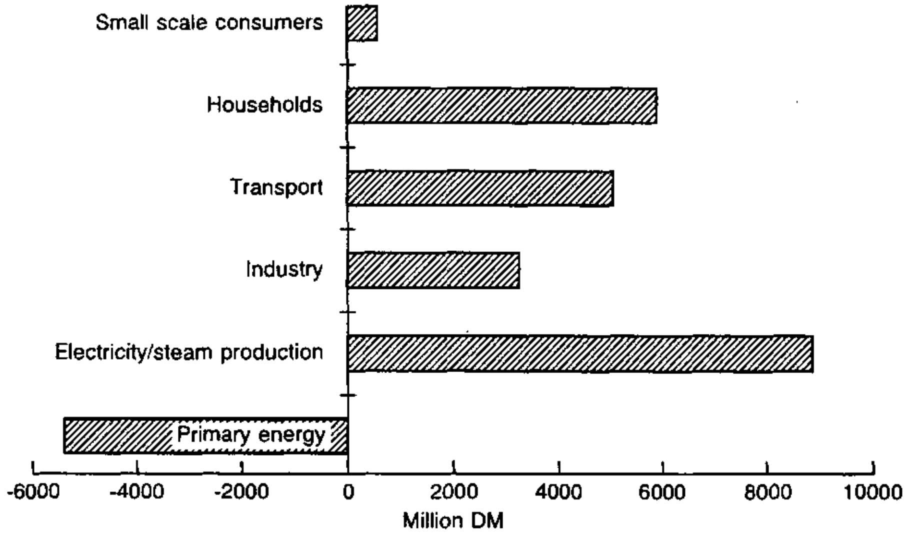

FIG. 9. Shares of sectors in the costs for CO_2 reduction by the year 2005.

replacement of coal or oil by natural gas, especially in the conversion sector. In the reduction case, CO_2 is reduced in all sectors. The greatest share of CO_2 reduction (25%) comes from the conversion sector and is 53%. The other shares are: residence sector 26%, industry 13%, small consumers 6% and transport 2%.

The total direct costs for reduction of CO_2 emissions by the year 2005 amount to about 18.2×10^9 DM (1989), which is about 0.5% of the assumed GDP in that year. The sectoral shares are very different (Fig. 9). The adjustment of the conversion sector causes about 48% of the overall costs. The costs incurred in the second largest sector, the households, amount to about 32%. Transport and industry bear about 28% and 18% of the total costs. Only the primary energy sector shows a cost reduction of about 5.4×10^9 DM (1989). This is mainly due to the reduced domestic mining of fossil energy carriers, but it is also due to the reduction of energy imports caused by the use of low fuel consumption motor-cars in the private sector.

The marginal costs of CO_2 reduction amount to about 350 DM per t CO_2, whereas the average costs are about 150 DM per t CO_2.

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CLIMATE CHANGE MITIGATION STRATEGIES IN GERMANY
Integrated dynamic approach to the year 2020

P. SCHAUMANN, S. MOLT, E. LÄGE,
W. RÜFFLER, U. FAHL, A. VOSS
Institute of Energy Economics and Rational Use of Energy,
University of Stuttgart,
Stuttgart, Germany

Abstract

CLIMATE CHANGE MITIGATION STRATEGIES IN GERMANY: INTEGRATED DYNAMIC APPROACH TO THE YEAR 2020.

A national strategy for mitigation of the consequences of a climate change has to take into account the national economic welfare. With regard to this, a cost effective greenhouse gas mitigation strategy that aims at maximizing the amount of CO_2 reduced per German Mark invested is of paramount importance. The climate change, a sound economy, a sustainable environment and security of energy supply have to be taken as a unit, on which political and economic decisions should focus. The study presents different climate change mitigation options aiming at achieving environmentally and economically compatible solutions for abatement of energy related greenhouse gas emissions in Germany.

1. INTRODUCTION

Impairing the stability of the global climate system, the emissions of greenhouse gases into the atmosphere are threatening fundamental conditions for the existence of mankind. Today, the problem is mainly caused by the high level of consumption of fossil fuels in industrialized countries. Primarily the wealthier countries are called upon to develop greenhouse gas mitigation strategies on a national basis, even if there are still large uncertainties regarding the extent of global climate change and its possible impacts on the environment. Since the energy sector is the largest single contributor to greenhouse gas emissions in industrialized countries such as Germany, a study was set up to analyse possible paths for the future development of the national energy system to limit greenhouse gas emissions.

2. EMISSIONS OF CO_2 IN GERMANY

After reunification, Germany inherited a large number of environmental problems from the area of the former German Democratic Republic, particularly

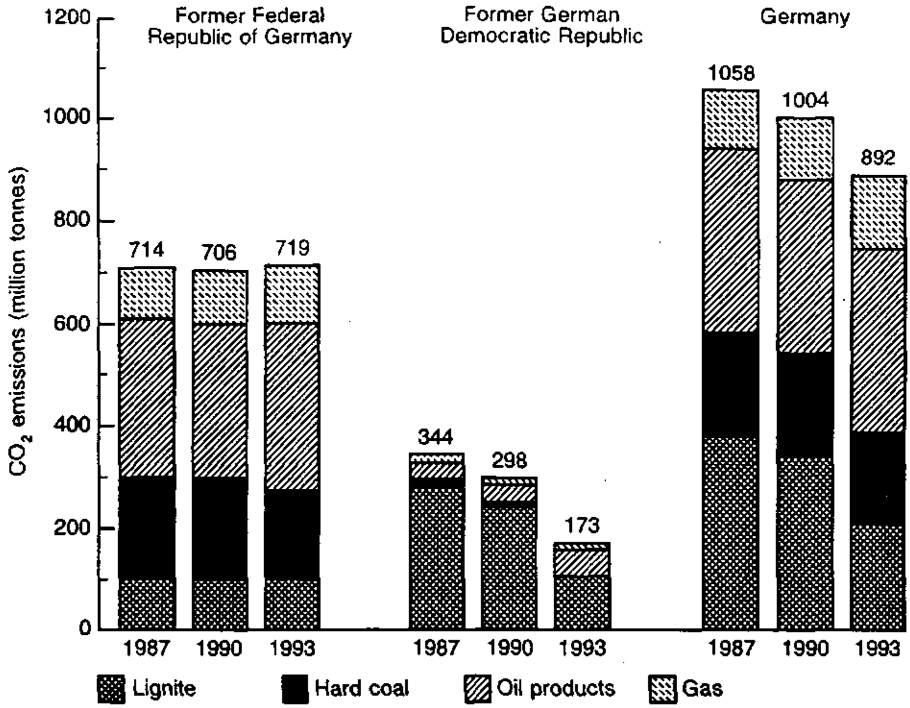

FIG. 1. CO_2 emissions in Germany (historical data).

regarding greenhouse gas emissions. Taking the CO_2 emissions as an example, the total combined emissions of the former Federal Republic of Germany and the German Democratic Republic were over 1000 million tonnes of CO_2 in 1987, ranking Germany fourth among all countries in the world regarding CO_2 emissions (right behind the United States of America, the former Soviet Union and China).

The former region of western Germany contributed roughly two thirds of these emissions in 1987 (see Fig. 1). The development of the emission levels in western Germany shows a tendency of stabilization and a slight decrease since the early 1980s. This was accomplished by changing economic patterns, by substantial improvements in energy efficiency, and by increased use of nuclear energy and natural gas, even though that period was characterized by economic growth rates of 2–3% annually and an internationally high level of economic output per unit energy input.

In contrast to this, the energy system of the former German Democratic Republic suffered from a low energy efficiency and a high reliance on lignite, emitting 21.2 t CO_2 per capita — a value that set a poor world record in 1987. The overall CO_2 emission levels increased by approximately 2% annually during the 1980s. The steep drop in CO_2 emission levels is the result of the drastic decline in industrial and lignite mining activities after reunification in 1990.

2.1. Political framework and characteristics of the scenarios

In order to guarantee a certain degree of independence of oil and gas imports, the former Federal Republic of Germany pursued an energy policy of 'national supply side security'. This resulted in a relatively large percentage of consumption of domestic hard coal, which was mainly used for electricity generation. Since the extraction costs of coal in Germany are currently triple those on the world market, they have to be subsidized. The energy supply of the former German Democratic Republic relied to about 90% on domestic lignite, since the bills for imports had to be paid in foreign exchange.

The Federal Government has committed itself to reduce the energy related CO_2 emissions by 25% (based on 1990 emission levels) by the year 2005. This target is based on the recommendation of the Enquete Commission for the Protection of the Earth's Atmosphere of the German Bundestag. In addition, the Enquete Commission has proposed a 50% reduction of CO_2 emissions by the year 2020.

It is obvious that the future national coal policy will have a strong influence on how and at what costs the desired reduction goals can be achieved. Because the future national coal policy is still under discussion, the present study assumes reduced levels of minimum consumption of domestic hard coal and lignite.

Even more controversial is the issue of the future role of nuclear energy in Germany. At present, 30% of the electricity is generated in nuclear power plants. To capture the different views of the future role of nuclear energy, this analysis is based on three different assumptions: a constant nuclear capacity, a phase-out of nuclear energy by the year 2005, and an expansion of nuclear capacity if this is economically justified.

Four scenarios were constructed to analyse the CO_2 mitigation strategies under different political assumptions. The 'business as usual' scenario (**REF**), with no CO_2 reduction goal, serves as a reference case for the three climate protection scenarios for which a CO_2 reduction of 25% by the year 2005 and of 50% by the year 2020 is targeted.

The basic characteristics of the four scenarios are as follows:

- **REF:** a 'business as usual' scenario with the protection of domestic coal and constant nuclear capacities of currently installed 22.5 GW for all years (reference case);
- **K1:** a climate protection scenario with the protection of domestic coal and constant nuclear capacities;

- **K2:** a climate protection scenario with energy policy restrictions (phase-out of nuclear energy, restrictions on the use of domestic coal);
- **K3:** a climate protection scenario with lifted energy policy restrictions (i.e. no restrictions on the use of domestic hard coal and lignite, and no restrictions on the use of nuclear energy).

2.2. Methodology and macroeconomic assumptions

Different abatement strategies are being analysed by a technico-economic energy system model with a linear optimization algorithm. The model employed represents a technology oriented bottom-up approach. This multiperiod and multiregional approach allows reduction technologies to be identified and assessed by the criterion of their cost efficiency. The objective function evaluates the minimum of the total discounted system costs, integrated over all time periods and all regions.

All technologies in the model are described by a set of parameters (costs, technical potentials, emissions, efficiencies, etc.). A relatively stable annual economic growth of 2.6% in the period until the year 2005 — mainly due to the catching-up process of the eastern German economy — is assumed. Annual growth rates of 2.1% between 2005 and 2020 are presumed. The population is projected to remain constant at approximately 80 million people. The world market energy prices for crude oil and natural gas are assumed to rise moderately, by a factor of two, until the year 2020.

The basic macroeconomic assumptions as well as the estimated levels of energy service demand are applied exogenously to the model and remain unchanged for the scenarios considered.

2.3. Reduction strategy evaluation

The study results suggest that a 50% reduction of CO_2 by the year 2020 is feasible for Germany. This reduction can be attained with technologies that are already available or are known to become available in the next thirty years. The 50% CO_2 reduction target can be achieved even without the technological option of nuclear energy as a carbon free energy carrier. Allowing the option of nuclear energy to contribute to the CO_2 reduction, the 50% CO_2 reduction target can be achieved at significantly lower costs of energy supply than in the other abatement scenarios considered.

Figure 2 shows the primary energy consumption by energy carriers in the years 1990, 2005 and 2020. For each year the results of scenarios **K1**, **K2** and **K3** are shown. Because of the 50% reduction goal, primary energy consumption decreases in all three scenarios. The role of nuclear energy is defined by the energy policy restrictions. Compared with the ‘business as usual’ case, nuclear energy remains

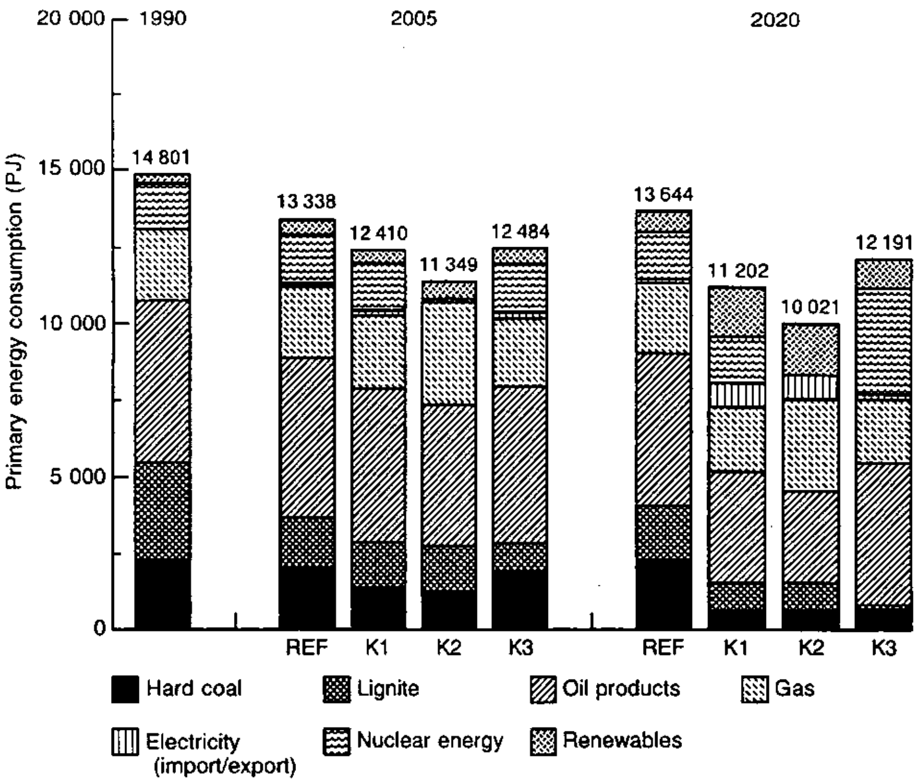

FIG. 2. Primary energy consumption.

constant in scenario **K1**. After the year 2005, nuclear energy cannot contribute to the primary energy requirements because of the phase-out of nuclear energy (in scenario **K2**). In scenario **K3**, however, with no restrictions on nuclear energy, its share increases by about 1.4 GW(e)/a, to a value of 3500 PJ (29% of the total primary energy consumption) in the year 2020. The renewable energy carriers gain in importance and contribute 14% (scenario **K1**) and 16% (scenario **K2**), respectively, to the primary energy requirements (especially electricity generation by windpower plants, solar power and hydropower plants, as well as incineration of waste). Natural gas replaces nuclear energy in scenario **K2** and increases to a share of 29% (2930 PJ) in the year 2020.

The additional system costs and the marginal CO_2 abatement costs can be used to evaluate the economic implications of the different reduction strategies. The marginal costs can be interpreted as the costs that are required for the reduction of the last unit of CO_2 (these costs are determined by the technology that is used to

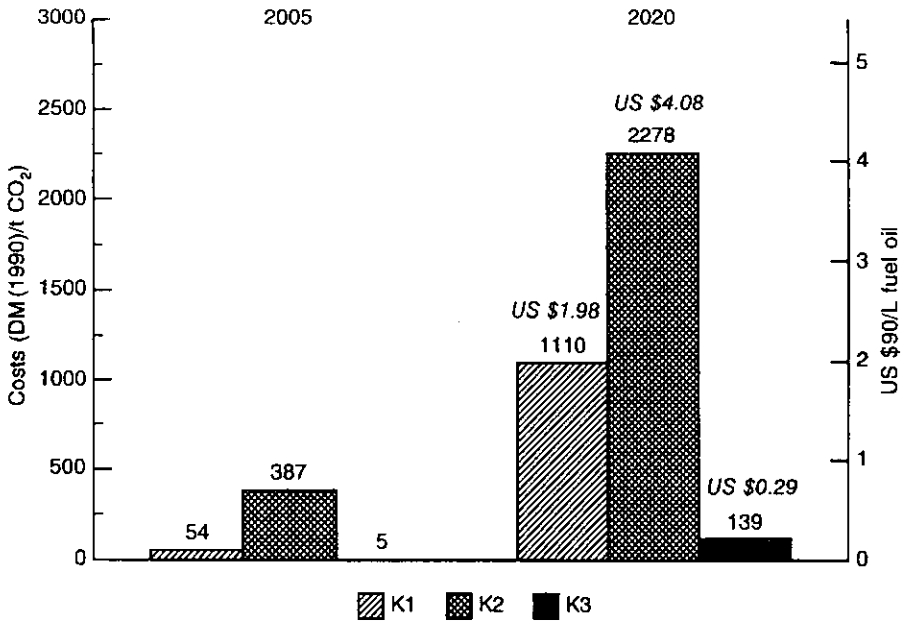

FIG. 3. Marginal costs of CO_2 reduction.

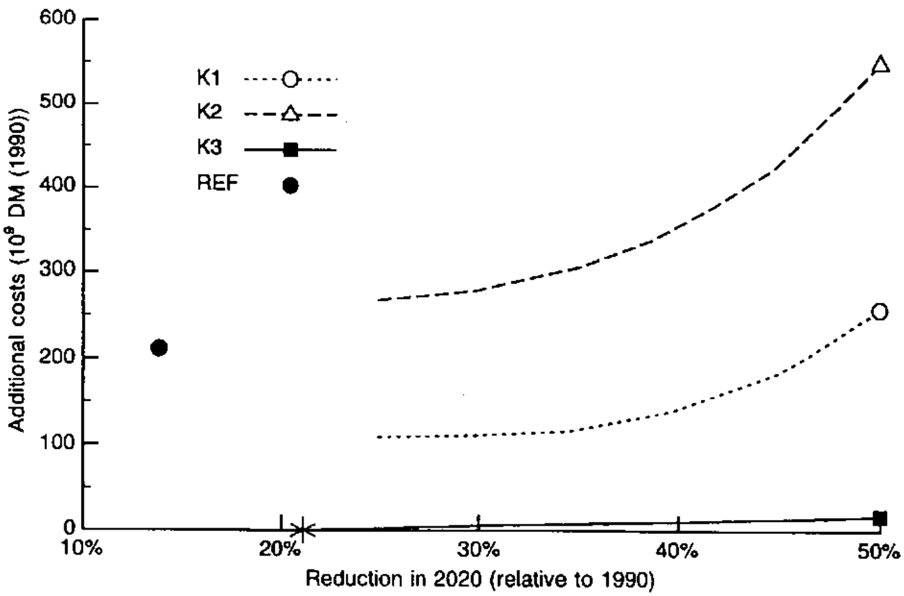

FIG. 4. Additional costs of CO_2 reduction.

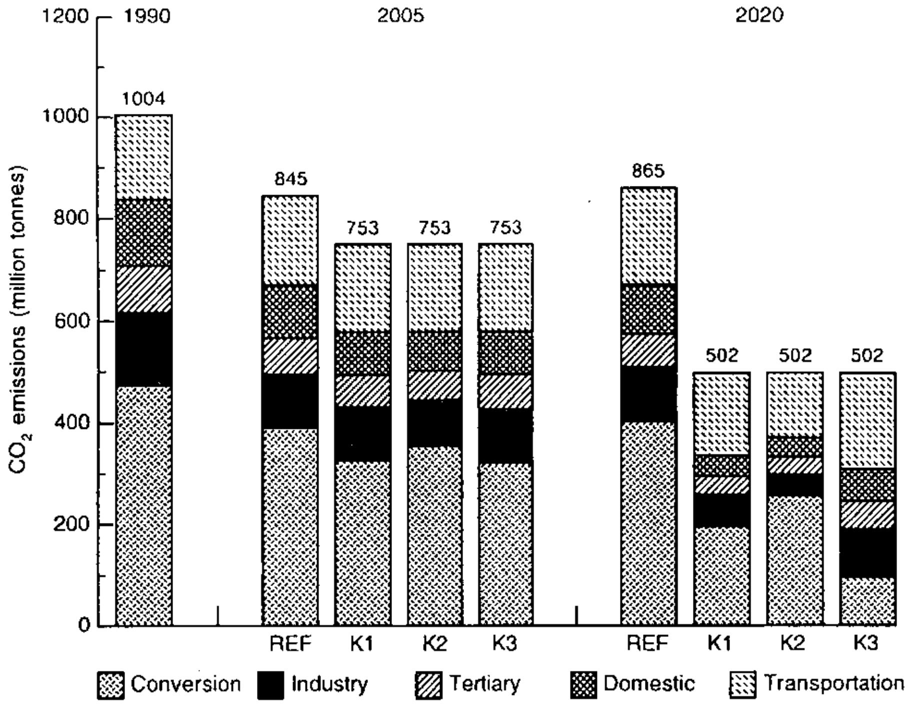

FIG. 5. Total CO_2 emissions in Germany for the period 1990–2020.

reduce this unit of CO_2). The marginal costs range from about 139 DM (1990) per tonne of CO_2 in the year 2020 (scenario **K3**) to about 2278 DM (1990) per tonne of CO_2 (scenario **K2** — see Fig. 3). To get a better impression of these values, they are also presented in US $ per litre of fuel oil. Figure 4 shows the additional system costs of the reduction scenarios **K1**, **K2** and **K3** in relation to the reference case.

Compared with the 'business as usual' case, the results indicate that the reduction targets could be achieved even with considerably lower system costs if no policy restrictions were applied. Compared with the 'least-cost' strategy (**K3**), a nuclear phase-out policy with simultaneous protection of the domestic coal industry (**K2**) would be faced with additional costs in the range of 550×10^9 DM (1990) until the year 2020 (32×10^9 DM (1990) per year) to achieve the same CO_2 reduction.

Figure 5 shows the computed CO_2 emissions in Germany for all scenarios. The reduction goals of scenarios **K1**, **K2** and **K3** are 25% in the year 2005 and 50% in the year 2020 (related to 1990 emission levels). The increased level of CO_2 emissions from the conversion sector in scenario **K2** is due to the enhanced use of gas fired power stations which are built to replace nuclear power plants. The removal of the coal restrictions and the restrictions on nuclear energy lead to a decrease of CO_2 emissions from the conversion sector of about 80% (related to 1990). In scenario **K3** the transportation sector holds the largest share in the year 2020, with 37.5% (190 million tonnes of CO_2). The tertiary sector reduces its CO_2 emissions in the year 2020 by 41% (scenario **K1**) and by 48% (scenario **K2**), related to the levels of the **REF** scenario in the year 2020.

3. CONCLUSIONS

With a 'business as usual' strategy (as represented in the **REF** scenario) the CO_2 mitigation targets of 25% by the year 2005 and 50% by the year 2020 cannot be achieved.

A 50% reduction of CO_2 by the year 2020 (including a 25% reduction by the year 2005), based on the 1990 emission levels, is technically feasible. However, the costs depend strongly on the mitigation strategy and are determined by the assumed coal and nuclear policies.

A 'least-cost' strategy without policy restrictions would allow the reduction targets to be achieved with considerable cost savings compared with the 'business as usual' strategy.

The protection of the domestic coal industry and a phase-out of nuclear energy would result in additional costs of about 550×10^9 DM (1990) until the year 2020 to reach the desired reduction targets.

The CO_2 reduction effect of a carbon tax will strongly depend on the future policy for domestic coal and nuclear energy.

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POSTER PRESENTATIONS

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ENVIRONMENTAL IMPACTS OF THE POWER SYSTEM
Case study for Argentina, 1990–2010

C.E. SUÁREZ, N. DI SBROIAVACCA, A. DOBRUSIN, G. HASSON
Instituto de Economía Energética,
San Carlos de Bariloche, Argentina

Abstract

ENVIRONMENTAL IMPACTS OF THE POWER SYSTEM: CASE STUDY FOR ARGENTINA, 1990–2010.

The choice of electricity supply strategies normally has a strong impact on a country's energy situation; at the same time it can affect the physical and human environment in which the activities of the electric industry are carried out. As is the case with other economic activities, the decision process, particularly regarding the expansion of facilities, is influenced by a set of factors, among which institutional organization and regulation of the activity are of increasing importance. In fact, the leading role of the State in the provision of electricity in nearly all countries has obscured the importance of these aspects in the choice of supply strategy. Because of the evident worldwide tendency to restructure this industry, which involves a substantial change in the role of the State, it is advisable to revise analysis methods and instruments that help in decision making in the light of the new situation caused by the changes. For this reason, and in the context of the DECADES project, it was judged opportune to analyse the prospects of the Argentine electric system, whose organization has been drastically altered during this decade, along the lines of the reforms put into effect in the United Kingdom and encouraged by multilateral credit organizations, particularly the World Bank. The object of this case study is, therefore, to reflect the environmental and energy effects of the changes in electricity supply strategies made by new plant operators in comparison with the policies that were in force until the beginning of the 1990s and, at the same time, to analyse the relevance of the use of certain methods and instruments in decision making in the electric industry under the new organization.

1. INTRODUCTION

In connection with the two objectives covered in this study, it is of interest to provide an analysis of the Argentine electric sector. Regarding electricity supply strategies during the last 30 years, Argentina has sought to achieve self-sufficiency in oil supply, which in the electric industry has led to a weaker dependence on oil products, a greater use of natural gas in thermal power stations, utilization of the country's hydroelectric resources and development of nuclear power. After the reform of the electric system in Argentina and in the absence of specific incentives, private electricity generators indicated that their decisions regarding expansion of the electric system would be very different from those taken previously.

Regarding methodologies, the partitioning of the electric industry into sectors and the promotion of competition on the electricity market have rendered difficult the expansion planning for the electric industry. Under the new conditions, it is not possible to use optimization methods and models to obtain a picture of the actual decision criteria of the different groups involved, which, moreover, have many connections with other energy activities.

It is important to take into account that the institutional and regulatory reform of the electric sector in Argentina is part of an economic restructuring process, which comprises all energy activities and which aims at opening up the economy and including it in the international markets on the basis of competitiveness. With regard to the historical situation in Argentina, the changes that have taken place are profound, exceeding the fluctuations of the Argentine economy in the last 60 years. The expected consequences of these structural economic changes are summarized in the economic and energy scenarios that provide the framework for this analysis of electricity supply strategies.

2. CHOICE OF ANALYSIS METHODS AND INSTRUMENTS

In the past, decisions regarding expansion of the electric sector in Argentina were the subject of careful planning, including all electric companies under the leadership of the State Energy Bureau, which was responsible for approving the plans submitted. These plans were only occasionally an integral part of the analysis of the whole Argentine energy system, but they always responded to the energy policies in force.

Since the beginning of the 1970s, the national electric companies (reporting to the Government) adopted a joint approach to the development of methods and models for planning of electricity supplies. This co-operation of different companies led to the adoption of a set of common models which, over two decades, permitted joint optimization of electrical expansion and, to a certain extent, obviated conflicts between companies regarding market predominance.

From a methodological point of view, the actual meaning for society of partial optimization of the energy system and the resulting assignment of resources could be disputed. However, there is no doubt about the need for a systematic analysis of the electric industry, as distinct from an analysis of the possible characteristics of its institutional organization.

Nevertheless, the institutional structure and the operating rules of the electricity market have an important impact on decisions regarding investments. In this respect, the vertical segmentation of the electric industry and the diversification of enterprises render a systematic analysis dificult; it would be necessary to define precise co-ordination mechanisms and to submit the case to some type of arbitration, in order to enable general objectives to be placed above the interests of single companies. Establishment of competitive markets or promotion of competition on the electricity market are incompatible with co-ordination mechanisms, and integral planning of the electric system might not be possible.

Since the reform of the Argentine electric system is based on diversification of the industry and on promotion of competition, the types of model traditionally used in Argentina to define expansion have been considered inappropriate in the new situation. An integral analysis of the electric sector would have to be based on the use of models representing the expected behaviour of the different groups participating in the electric industry.

It was therefore decided to use a simulation model that represents the investment strategies of private entrepreneurs and that allows the energy and environmental effects of the probable evolution of the sector to be analysed. From among the group of models surveyed by the DECADES project, the LEAP model was chosen as an appropriate tool.

It is well known that LEAP can be used for specification of the interconnection of a set of energy activities. This feature is particularly appropriate for measuring the impact of the electric sector on the activity level of the other energy sectors and on the reserves of the different primary resources.

This model was also used in the simulation of the operation of the energy system in the case of a continuation of the hydro-nuclear strategy for electricity supply that has been maintained in Argentina over the last three decades. The results of a choice of hydroelectric power stations correspond to the results of optimization models that were obtained previously when plans for electricity generation were drawn up; these plans never went into effect because of the reform of the Argentine electric system.

The environment module of LEAP can be used to obtain the aerial emissions of different types of gas caused by the energy system as a whole, specifying the emissions due to each type of activity. Consequently, by comparing the emissions of the different electricity supply strategies, it will be possible to determine the direct and indirect differential environmental impacts of dropping the hydro-nuclear strategy.

2.1. Economic and energy scenarios

The effects of the changes that have occurred recently, both in the economy and in the energy sector of Argentina, can be studied by considering two scenarios. In formulating the economic scenario, an optimistic hypothesis has been adopted with respect to the evaluation of the country's economy in the international context.

The optimistic aspect of this scenario is the assumption of an improvement in the country's conditions of access to financial sources within the framework of a larger growth of the world economy, with fewer obstacles to the participation of primary and agro-industrial products in international markets.

In this context, it was assumed that the Argentine economy will return to the growth process that was interrupted in the mid-1970s, and that this growth will be mainly due to export activities. Participation in international markets would be achieved by improving productivity and increasing efficiency, including the energy sector. The gradual integration of MERCOSUR would facilitate economic co-operation with other countries in the region and would contribute to a progressive reduction of costs. This realignment of production activities would intensify economic concentration, leading to a regressive distribution of income and to greater social antagonism, which would affect consumption levels.

The expected evolution of the Argentine economy will have an impact on the final energy consumption, in addition to the effects of the energy reform, particularly regarding energy price policies and the commercial strategies of private operators. These forecasts have been included in the energy scenario, the outstanding features of which are described below (see Table I).

As regards the commercial strategies of private suppliers of energy services, it was assumed that attention will be focused on increasing sales by gaining new customers in the areas served and by limiting expansion of the existing networks to profitable areas. This commercial strategy will affect particularly the energy sources distributed by means of networks, limiting the possibilities of larger service coverage by natural gas and electricity.

TABLE I. GROWTH OF THE MAIN ECONOMIC VARIABLES (ANNUAL AVERAGE RATES)

Items	Optimistic scenario	
	1992–2000	2000–2010
GDP	3.0	3.8
Population	1.3	1.3
GDP/inhabitant	1.7	2.5
Investment	5.1	6.8
Imports	0.2	4.5
Exports	5.3	6.0
Debts	4.0	0.5
Exchange terms	0.5	1.0

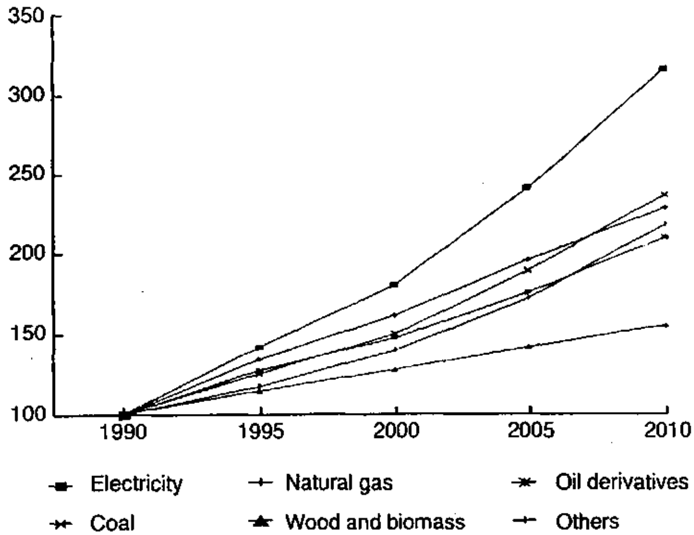

FIG. 1. Growth of final energy consumption by source (1990 basis).

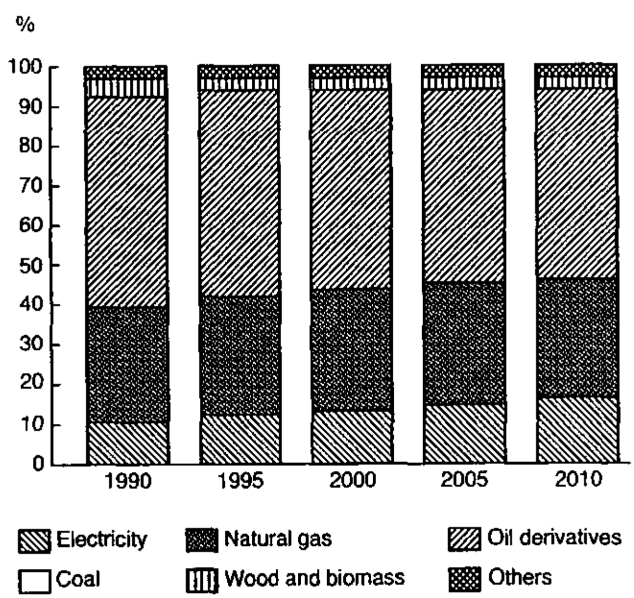

FIG. 2. Share of energy sources in the final energy consumption.

The combination of these factors could lead to a growing dichotomy of final energy consumption in the residential sector. Furthermore, the lower income social groups would experience a degradation of the quality of energy products and a decrease in the satisfaction of their needs. On the other hand, the affluent classes would act as driving factors in consumption growth, which would lead to lower energy prices and to greater access to new uses and appliances.

The effect of this situation in the passenger transport sector, with a larger incidence of individual transport, could be reinforced by elimination of railway subsidies upon privatization of the services and by favouring collective highway transport (buses).

In the goods production sectors, the increase in energy prices will enhance the tendency towards a more rational use of energy in view of the search for greater production efficiency that is essential for successful participation in international markets. In the manufacturing industry, the electricity demand should grow faster than the availability of fuels because of the preponderance of the metal-mechanical branch. Regarding production of primary resources, the development will be more dynamic than in the past because of the greater use of advanced technologies, which is closely connected with the importance of export for the Argentine economy.

According to these assumptions, it was estimated that final energy consumption will grow at a rate of 4.2% per annum until the year 2000 and at 3.9% per annum in the period 2000–2010. These estimates are based on a product fluctuation of 1.14 and 1.02 for 1990–2000 and 2000–2010, respectively, in spite of the decrease in growth of the energy consumption observed in recent years (see Figs 1 and 2).

The most dynamic development would take place for electricity, with a sustained accumulated growth in demand close to 5.9% per annum for the whole period under analysis; the share of electricity should increase from 11% to 16.2%. However, the share of natural gas should remain practically the same as in 1990, and the decline in oil products should become more pronounced. This increased growth of electricity demand compared to the demand for other energies is the result of the assumed type of economic growth and does not imply a change in the part played by electricity in the satisfaction of energy requirements.

In this connection, it should be pointed out that the development of natural gas transport and of the distribution infrastructure in Argentina as well as the favourable price policy have prevented penetration of electricity in caloric uses, except for those industrial processes where the production quality is improved by the use of electric furnaces. The optimistic scenario (Table I) assumes that the historical role of natural gas is maintained even though the deregulation of the gas market at the well-head and the privatization of the transport and distribution sector will lead to a large increase in its price. In spite of this, it is estimated that, in the medium term, gas will continue to be competitive in caloric uses compared with electricity, particularly in view of the high level of development of the infrastructure. It is even possible that gas distribution companies may want to expand their participation in the market in areas that were so far considered to be the domain of electricity, for example air conditioning.

2.2. Definition of electricity supply strategies

For the purpose of this study, two alternative strategies for electricity supply of the Argentine system in the period 1990–2010 have been analysed.

The first strategy, called the thermal alternative, is based on the assumption that the future expansion of electricity generation in the country will use exclusively conventional thermal power stations (open cycle gas turbines and combined cycle power stations), except for the hydroelectric and nuclear power stations that were under construction at the time when the reform was put into effect and the shut-down of which has to be handled by official institutions.

The second strategy, called the hydro-nuclear alternative, is based on the assumption that the policies applied by the State in the electric sector in the last 30 years will be maintained, i.e. that utilization of the country's hydroelectric resources will be promoted and that nuclear energy will also be developed.

2.2.1. *The thermal alternative*

Once the electricity market has absorbed the additional supply from the hydroelectric and nuclear power stations currently under construction (the estimated date is around the year 2000), expansion of electricity generation will be implemented exclusively by private operators. In accordance with international experience (especially in the United Kingdom) and in accordance with the decisions already taken by private investors in Argentina, the expansion of generation capacity will be based on technologies with low capital intensity, which implies abandoning the hydro-nuclear strategy of the past. Even though private investors in Argentina are encouraging the installation of open cycle gas turbines, it is assumed that, after the year 2000, expansion will be based on combined cycle power stations, preferably using natural gas.

In this strategy the uncertainty is shifted to the gas industry and, more specifically, to mining and exploration activities, regarding the capacity of the industry to incorporate new gas reserves that would allow the production to be increased in order to meet future final and intermediate demands, maintaining a reserve/production ratio of 11.5 years for natural gas and of 9.5 years for oil. To fulfil this objective, it would be necessary to discover new oil reserves of a volume equivalent to 3.2 times the present levels and gas reserves of a volume of 1.8 times the present levels.

In view of this uncertainty, it was considered advisable to analyse two versions: one version is based on the assumption that private operators are interested in investing in explorations and that new reserves (large ones) will be discovered; the other version assumes that only small reserves will be discovered; for this version it is necessary to adapt the electrical equipment in order to adjust to a lower availability of natural gas, leading to greater consumption of oil products. At any rate, the low reserve version for natural gas would mean that the level of gas discoveries in recent years in Argentina would have to be increased by 20%.

In both versions, the electric system would require installation of about 12 000 MW in new conventional thermal power stations, which would be added to the 5500 MW to be installed in the power stations being constructed with State funds. Regarding work in progress, 14% of the total would be needed for the third nuclear power station and the remaining 86% for three hydroelectric power stations which, according to their construction timetable, should start up after the year 1995.

2.2.2. *The hydro-nuclear alternative*

Because of delays in plant construction and the forecast economic growth in Argentina there will be some problems of electricity supply in the first five-year period analysed. In this strategy it is assumed that it will be possible to speed up the

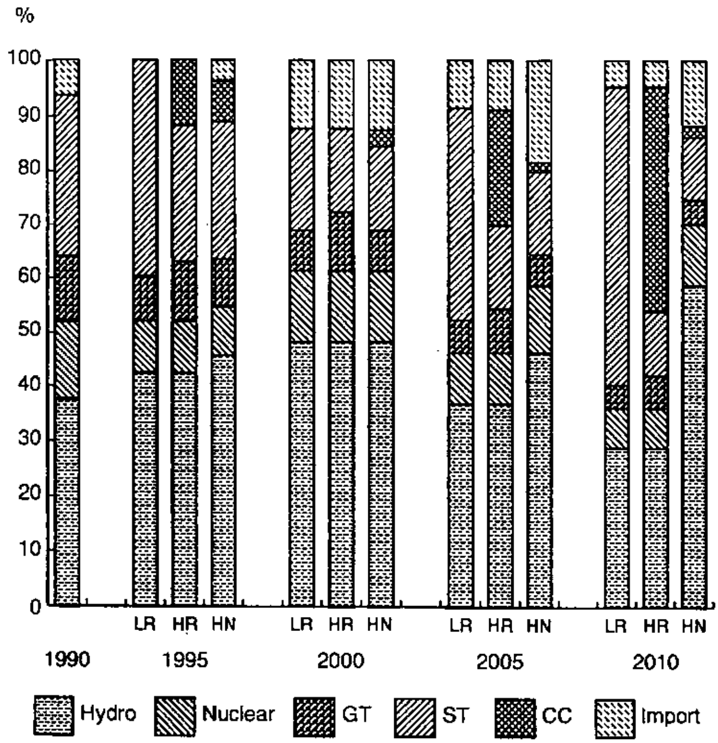

FIG. 3. Structure of electricity supply within the public service sector. GT — gas turbine, ST — steam turbine, CC — combined cycle.

operational rhythm of one of the hydroelectric plants; nevertheless, installation of around 1000 MW in conventional thermal power stations is required. The solution adopted, which is considered to be the most interesting option, is to complete combined cycle plants, starting with the existing thermal power stations.

In order to meet the growing electricity demand after the year 2000, a group of power stations was selected whose economic competitiveness compared with that of other generation options had been demonstrated in different electric planning studies. The total capacity of these power stations is more than 11 000 MW, including advanced exploitation in mountainous zones and power stations having a larger plant factor situated near rivers in plains.

However, because of the relatively high load factor of the Argentine system (63%), additional base generation would have to be provided; three new nuclear power plants would be installed in the last decade analysed. Following the latest official plan, it was assumed that the technology of these plants would be the same as that of other nuclear plants in Argentina (natural uranium reactors with heavy water as moderator), but that the size of the modules would be considerably reduced.

The electric power of the nuclear plants in Argentina increased from 370 MW(e) for the first plant (Atucha I) to 745 MW(e) for the unit under construction (Atucha II). On various occasions it was pointed out that the modules selected, while corresponding to the global supply tendency of this type of plant, were too large for the demand characteristics in Argentina, especially for locations outside the metropolitan grid. In view of this, the National Energy Bureau decided towards the end of the 1980s that future nuclear power plants should have modules of 345 MW(e). Therefore, in the present study it is assumed that new nuclear power plants will have modules of this capacity.

Figure 3 shows the evolution of the structure of electricity supply within the public service sector, taking into account the three scenarios analysed.

3. CONCLUSIONS

As a result of this study, in which different alternatives of electric installations for Argentina in the period 1990–2010 and some of their environmental impacts are analysed, we come to the following conclusions:

(1) The institutional scheme of the Argentine electric sector and its measures regarding the properties and the regulation of the electric system have a direct influence on the type and magnitude of the impacts on the natural and human environment.

(2) This influence is due basically to the existing criteria and guidelines for the electric system that is governed by an explicit planning scheme at the national level, with State enterprises forming the great majority.

TABLE II. EMISSIONS FROM ELECTRICITY GENERATION IN NUCLEAR PLANTS

Emissions	All scenarios	All scenarios	Thermal scenario	Hydro-nuclear scenario
	1990	2000	2010	2010
Tritium in air (TBq)	695	1058	1058	1762
Tritium in water (TBq)	750	1142	1142	1901
Noble gases (TBq)	749	1141	1141	1898
Solid low level wastes (m^3)	109	166	166	276

TABLE III. AREAS FLOODED BY BUILDING OF DAMS OF HYDROELECTRIC PLANTS

	All scenarios	All scenarios	Thermal scenario	Hydro-nuclear scenario
	1990	2000	2010	2010
Flooded area (10^3 ha)	298	360	360	1290
Installed hydropower (ha/MW)	45.82	37.14	37.14	69.26

TABLE IV. INHABITANTS DISPLACED BY BUILDING OF DAMS OF HYDROELECTRIC PLANTS

	All scenarios	All scenarios	Thermal scenario	Hydro-nuclear scenario
	1990	2000	2010	2010
Inhabitants displaced	30 000	63 450	63 450	72 180
Inhabitants per MW installed capacity	4.61	6.5	6.5	3.9
Inhabitants per GW·h	0.595	0.738	0.429	0.488

(3) The hypotheses used in designing the alternative socioeconomic scenarios are based on the 'normal' behaviour of each type of actor and on the decisions that were taken and/or are being taken in Argentina.

(4) For the case of Argentina in the period under consideration, the analysis shows the great inertia of the electric systems, particularly in the hydro-nuclear alternative. It can be seen that in spite of drastic changes of the regulatory and property regime of the electric system at the beginning of the 1990s, the system will continue to evolve largely in accordance with the previous rationale until the year 2000; therefore, the declining tendency of gas emissions (CO_2, SO_2, NO_x and particles) is continuing, with slight variations, in all alternatives. Incorporation of a new nuclear power plant leads to a significant increase (70%) in radionuclide emissions into air and water and to the production of radioactive wastes (Table II). In the case of hydroelectricity, the installation of three power plants (two in the plains and one in a mountainous zone) leads to an increase in the total flooded area; however, the specific coefficient continues to fall, until the year 2000, when it reaches a value of 37.1 ha/MW compared with 45.8 ha/MW in 1990.

As regards the population displaced by the building of dams for hydroelectric plants, in both alternatives the coefficient increases from 4.6 inhabitants per megawatt installed capacity to 6.5 inhabitants per megawatt in the year 2000; this is due to the incorporation of Yaciretá, which has a coefficient of 21.4 inhabitants per megawatt (Tables III and IV).

(5) The different effects on energy and on the natural and human environment of the two versions are clearly visible only in the period 2000–2010. As expected, in that period the thermal version leads to a substantial increase in gas and particle emissions from the electric system (Fig. 4). For the alternative assuming high reserves of oil and natural gas, the emission of CO_2 increases by 48.0%, that of NO_x by 38.0%, that of SO_2 by 75% and that of particles by about 230%.

(6) In the version assuming low natural gas and oil reserves, these increases are even larger, since, because of the lack of natural gas, thermal power plants will have to change from natural gas to oil. In turn, lack of domestic oil reserves will lead to a large increase in oil imports. In this case the emissions of SO_2 from the electric system will be five times higher, those of CO_2 will be four times higher, those of NO_x will increase by about 65% and those of particles will be three times higher.

(7) In the hydro-nuclear alternative, the tendency towards declining emissions will be maintained in almost all cases for the period 2000–2010, although at a slower rate than for the period 1990–2000. The emissions of CO_2 will be reduced by about 26% and those of NO_x also by about 26%. The emissions of SO_2 will remain constant, while the emissions of particles will increase somewhat less than in the version assuming high reserves.

(8) When indirect emissions due to the production, transformation and transport of the fuels used for electricity generation are added to the direct emissions, the

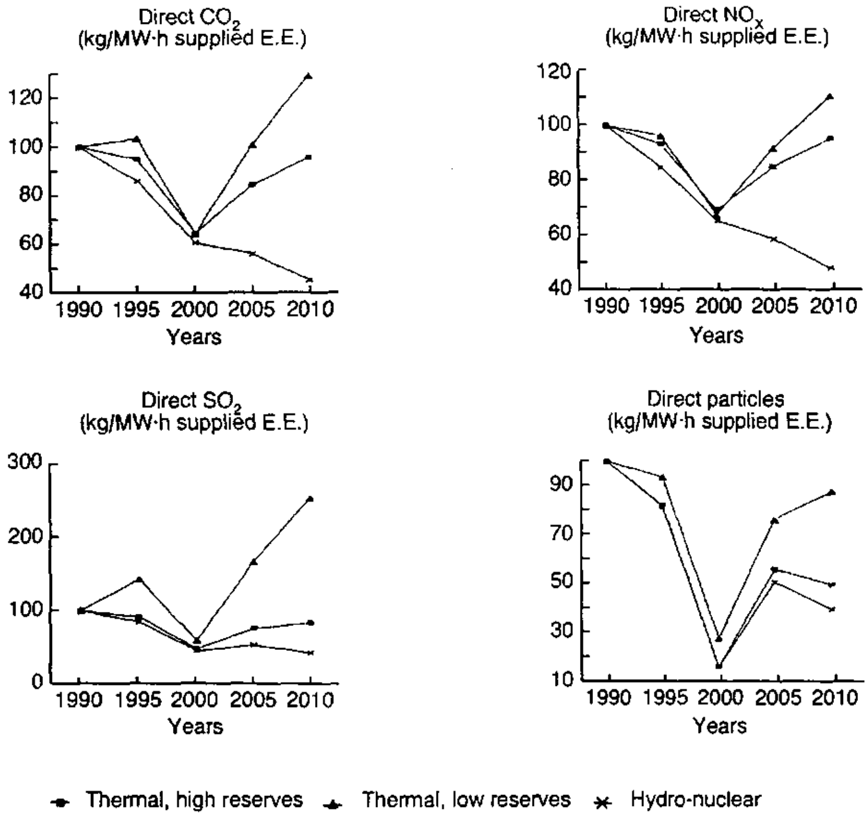

FIG. 4. Evolution of direct emissions (1990 basis).

evolution of the various emissions is similar for the different versions, but the changes are less pronounced (Fig. 5).

(9) The evolution of emissions from electricity generation beyond the year 2010 is alarming, showing an even greater increase in the different emissions of gases and particles.

(10) In the hydro-nuclear version, the release of radionuclides would increase by about 66.5%, since the direct emissions would remain practically constant, while in the thermal versions it would drop by approximately 40%. Nevertheless, the radioactive emissions by the year 2010 in the hydro-nuclear version would be 50% higher than those in the thermal version (1990).

(11) In the hydro-nuclear alternative the surface flooded per megawatt installed capacity is significantly increased (50%) because most of the power plants are located in plains. Conversely, the specific coefficient of displaced inhabitants per

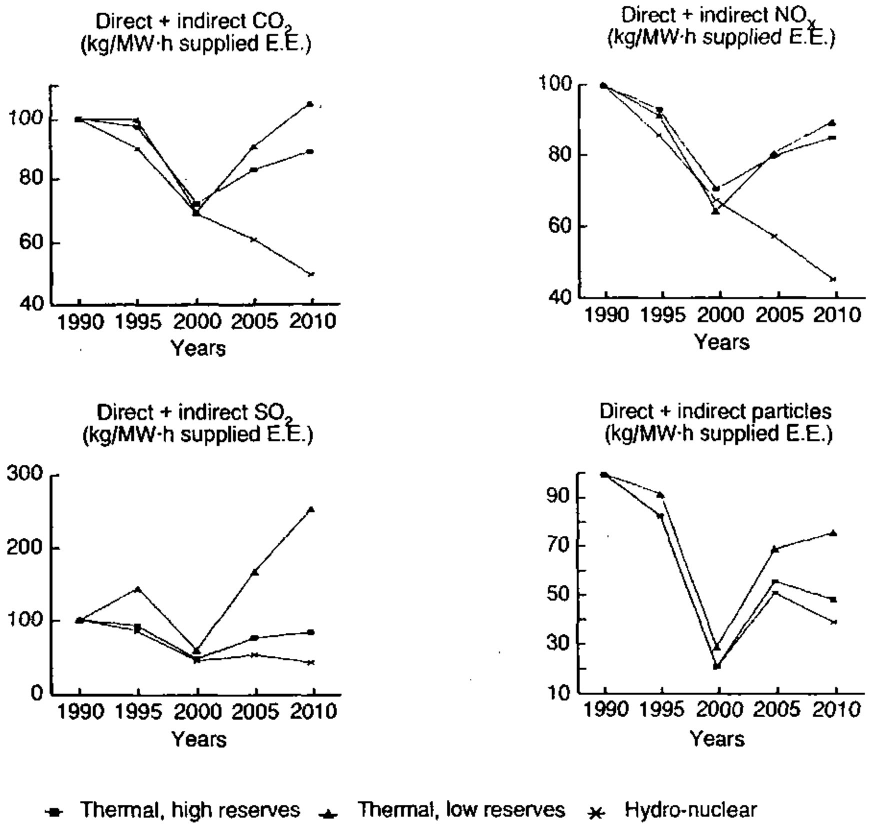

FIG. 5. Evolution of direct and indirect emissions (1990 basis).

megawatt installed capacity is less in the hydro–nuclear version than in the thermal version since the projects selected would be situated in sparsely populated zones and/or would have dams, which would greatly reduce their impact.

(12) For an evaluation of the importance and relative values of these alternative impacts it would be necessary to make a comparative economic evaluation of the different alternatives, which is beyond the scope of this study. The impacts of the hydro–nuclear alternative are basically of a local nature and can be controlled and mitigated to a great extent. On the contrary, CO_2 emissions cannot be controlled and their impact is of a global nature because of the greenhouse effect.

(13) From a methodological viewpoint, the LEAP model is, in general, a suitable instrument for simulating and identifying the direct and indirect effects of the various alternatives both for the electric system and for the whole energy system, from production to final energy use. For the electric system the direct and indirect

impacts of the different alternatives could be identified separately by assuming that the system was totally supplied with imported electricity; thus it was possible to calculate, by difference, the indirect impacts that would otherwise not be made explicit by the model. This mechanism is an alternative to the one used in the reference technology database (RTDB, DECADES) on intervening in the impacts throughout each of the different technological chains.

(14) As regards the specific impact coefficients of each source in each of the production/transformation/utilization activities, it was necessary to refer in most cases to international coefficients incorporated into the environment database of the LEAP model. A particular effort was made to determine coefficients of a local nature; this was possible for the different hydroelectric projects (flooded area and displaced population) and partially for the nuclear power plants in Argentina using natural uranium. More information would be needed in this field, in which the contribution of the IAEA could be fundamental.

(15) A methodological problem identified in this study was the great variety of values found in publications for one and the same energy source and activity (e.g. LEAP versus SIEE and OLADE versus RTDB), which could lead to quantitative differences in the results obtained. It is therefore proposed that, in the second phase of the study, the sensitivity of the results to the different values of the specific coefficients should be evaluated in order to appraise the magnitude of the problem.

In summary, it can be said that in this study it was possible to demonstrate and quantify suitably, in physical terms, the changes in the different types and amounts of negative impacts on the natural and human environment brought about by the institutional, juridical and property regimes. Moreover, it was possible to prove the adaptability of the LEAP model and its environment database to the study of these problems.

With regard to the RTDB/CSDB, a set of specific coefficients for hydroelectric and nuclear power plants in Argentina were determined; these coefficients were incorporated in these databases in the second stage of the project. However, this was not possible in the case of gaseous and particle emissions from thermal power plants since no systematic, homogeneous and reliable data for these coefficients exist in Argentina. The first measurements were begun only a few years ago.

4. RECOMMENDATIONS

On the basis of the above conclusions, it is possible to make the following methodological and energy policy recommendations:

This type of study should be continued in order to provide countries with suitable instruments for studying the problems of negative environmental impacts of the energy systems, particularly the electric systems.

The definitions of standard coefficients recognized at the international level for each energy source/activity/technology should be studied thoroughly and it should be made easier for countries, especially developing countries, to obtain specific coefficients of a local nature.

Energetic and integral electricity planning, independent of the property regime, is required in order to incorporate the long term environmental problems and to take into account the interests of present and future generations. Market forces alone, acting in a totally deregulated and non-planned system, cannot solve these problems. Furthermore, on many occasions, they generate self-defeating, inefficient decisions or else their environmental interest is not very strong.

Within the framework of the International Convention on Climate Change, new, additional financial mechanisms should be put into effect which would allow non-renewable energy sources and/or sources that do not emit greenhouse gases to be developed and which would permit suitable control and/or compensation of other negative environmental effects of a local nature.

It is imperative to promote and support the formation and training of adequate human resources in developing countries, in order to study and appraise the environmental problems related to energy and electricity generation.

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ANALYSIS OF ENVIRONMENTAL ASPECTS OF ELECTRICITY GENERATION OPTIONS IN BULGARIA

A. IOTOVA
National Institute of Meteorology and Hydrology,
Bulgarian Academy of Sciences,
Sofia, Bulgaria

Abstract

ANALYSIS OF ENVIRONMENTAL ASPECTS OF ELECTRICITY GENERATION OPTIONS IN BULGARIA.

The Bulgarian Case Study (BCS) is one of the 22 case studies carried out in the framework of the DECADES project. It was initiated in 1993 and started officially in April 1994. The main goal of the BCS is to illustrate the utilization of databases and other computerized tools for planning and decision making in respect of the electricity sector in Bulgaria. This is realized through incorporation of economic, technical and environmental characteristics of electricity generation options into the Bulgarian country specific database (BCSDB) following the structure of the RTDB/CSDBs in the IAEA DECADES project. Other computerized tools — the CO2DB and the RAINS and ENPEP models — are also used for the objectives of the BCS. Emphasis is placed on the analysis of environmental aspects of electricity generation options at local and regional scales through assessment of the related environmental impact.

1. INTRODUCTION

The paper informs on the Bulgarian Case Study (BCS), its objectives and goals, and the results obtained so far; it discusses the methodology and the computerized tools used in the research performed for the study and gives an analysis of the main results. The reference year in the BCS is 1991 because in this year the required data were relatively representative and complete. This year also marks the beginning of transition towards market economy in Bulgaria, even though most of the features of the previous planned economy were still present. The BCS considers recent electricity generation options in the country and some options for the near future.

2. METHODOLOGY AND TOOLS USED IN THE RESEARCH PERFORMED WITHIN THE BCS

The basic methodological concept for the research performed within the BCS is to apply a complex and integrative approach to the analysis of the environmental aspects of electricity generation options in Bulgaria. This concept is realized through adoption of and experiments with a few computerized tools for comparative assessment of different energy sources for electricity generation. The computerized tools proposed in the framework of the DECADES project have been reviewed [1]. The applicability of other relevant tools for the purpose of the BCS/DECADES project has also been examined. The reference technology database/country specific databases (RTDB/CSDBs), the CO2DB and the RAINS model have been tested to achieve the BCS goals. The application of the ENPEP model in Bulgaria is an alternative in the development of scenarios. A short description of these tools is given and their specific application in the framework of the BCS is discussed.

2.1. The Bulgarian country specific database and the DECADES RTDB/CSDBs

One of the basic tasks within the BCS is the design of a Bulgarian country specific database (BCSDB) as a realization of the RTDB/CSDBs in the IAEA DECADES project. Following the basic structure and the principles of the RTDB/CSDBs [2], data for the BCSDB have been collected and prepared. In parallel, experiments (for installation and operation) have been made with the RTDB/CSDBs software. Taking into account the specific problems in Bulgaria regarding data format and completion, the BCSDB is realized in EXCEL 5.0 form. Similar to the RTDB/CSDBs, the BCSDB contains basic technical, economic and environmental characteristics of the electricity generation options recently used in Bulgaria. Also included are the characteristics of other options that may be used in the near future — solar, wind and biomass. Thus, the BCSDB is a useful tool, both for research — within the BCS and similar activities — and for practical purposes, for application in Bulgarian energy planning and decision making institutions. Regarding the content of the BCSDB, Table I presents basic economic and technical characteristics of the fossil steam boiler (FSB) technology, which is being used most often in Bulgaria, as well as those of the projected fluidized bed combustion (FBC) technology and the solar photovoltaic (PV) crystalline technology. The FBC technology has a higher net efficiency and uses cheaper fuel than the FSB technology, while the main advantage of the solar PV technology is the zero cost of fuel. A more detailed analysis, comparing data from the BCSDB, could lead to useful conclusions for planning and decision making in respect of the electricity generation options in the country.

TABLE I. BASIC ECONOMIC AND TECHNICAL CHARACTERISTICS OF THREE TECHNOLOGIES

Technology	Status of development	O&M costs		Fuel costs	Book lifetime	Net efficiency	Possible equivalent full power
		Fixed (US $/kW)	Variable (¢/kW·h)	(¢/kW·h)	(years)	(%)	(h/a)
FSB (usually up to 200 MW)	Marketed	530	0.1	1.73	30	From 27.5 to 38.5, depending on the fuel	From 6000 to 7000, depending on the fuel
FBC (up to 200 MW)	Research	525	0.1	0.63	30	50	6000
Solar PV crystalline (up to 2 kW)	Pilot	—	—	0	20–30	13.5	1200

2.2. The CO2DB

A detailed examination of the documentation on the CO2DB [3, 4] makes it possible to clarify the question of its applicability to the BCS. Considering the emphasis on environmental aspects in the BCS, the CO2DB is suitable for the BCS mainly because of the better presentation of control techniques and of some new technologies for electricity generation. The CO2DB can be used for completion of the corresponding parts of the BCSDB, which is easy because of the similar types of data in both databases, i.e. data for the technical, economic and environmental characteristics of electricity generation technologies. Thus, the CO2DB appears to be a good additional source of data for completion of the BCSDB, especially for the parts containing control and projected technologies, since such data are still scarce in Bulgaria. Also, appropriate utilization of data from the CO2DB permits application of the experience of other researchers in the field of environmentally compatible energy and electricity technologies.

2.3. The RAINS model

It is appropriate to use the RAINS model in the BCS and to test its applicability to comparative assessment of different energy sources and of the environmental impact of electricity generation when considering the application of more computerized tools in the framework of the BCS/DECADES project. In view of the essential feature of the RAINS model as a scenario generating device that can be used for the development of scenarios to achieve long term environmental goals [5], experiments with the RAINS model (5.1 version) were performed within the BCS. Also, results from the application of the most recent versions of RAINS at the International Institute for Applied Systems Analysis (IIASA) [6] were studied in order to analyse the

TABLE II. COMPARISON BETWEEN DATA FROM THE EDB (RAINS MODEL) AND THE BCSDB

Fuel	Heating value (MJ/kg)		Sulphur content (%)	
	RAINS EDB	BCSDB	RAINS EDB	BCSDB
Lignite	10.5	10.5–10.9	3.0	~2.0
Hard coal	16.5–25.0	23.0–24.0	1.0–2.5	1.0–1.8
Heavy fuel oil	40.0	39.8	1.5–3.0	3.5

suitability of the model for the specific goals of the BCS and the DECADES project in general. Our research focuses on the ENEM (energy and emissions) module of the RAINS model — one of its three basic modules. The energy database (EDB) was developed and included in this module and the possibility of cost estimates provided. Some data presented in the EDB and in the BCSDB were compared and the agreement between them was found to be good. Table II illustrates this comparison.

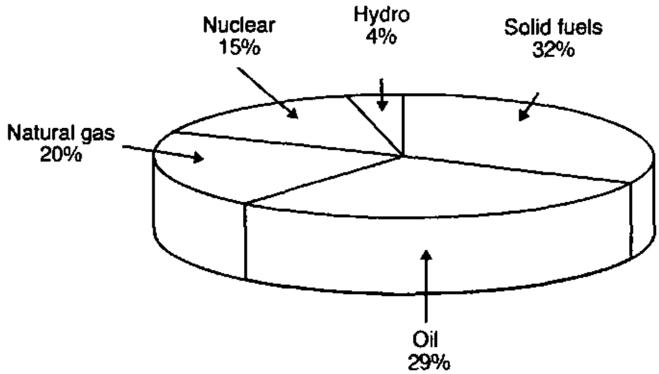

FIG. 1. Distribution of primary energy supply in Bulgaria in 1991.

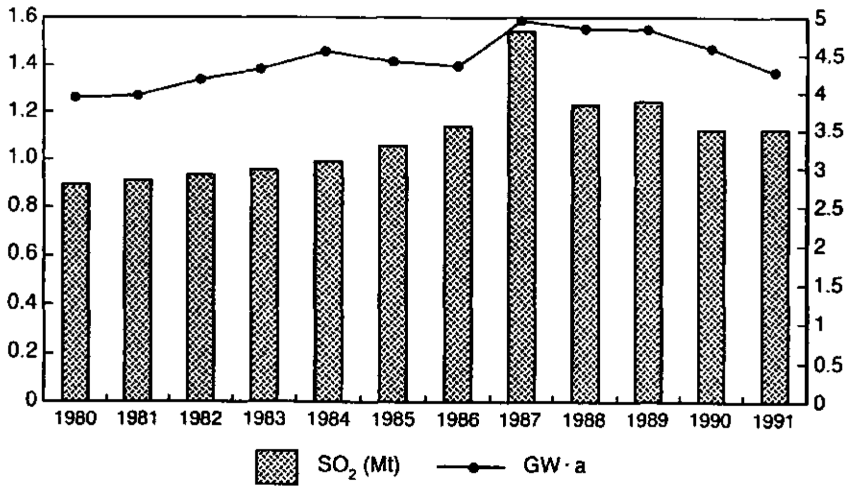

FIG. 2. Electricity generation and SO_2 emissions in Bulgaria from 1980 to 1991.

After examination of the advantages and limitations of using the RAINS model for the BCS goals, it was concluded that the advantages of this model are greater than the limitations to its use. Being an integrated assessment model and a technology oriented one, RAINS can be used successfully for analysis of the environmental aspects of electricity generation options in Bulgaria. The reasons for choosing the RAINS model are: its orientation to calculation of the SO_2 and NO_x emissions due to energy production; the provided cost estimates; the dominant role of fossil fuels for electricity generation in Bulgaria (Fig. 1) and the high SO_2 and NO_x emissions from thermal electricity production in the country. In Fig. 2 the total energy production (GW/a) over the period 1981-1991 is compared with the corresponding SO_2 emissions (Mt/a). The observed high level of SO_2 emissions is caused by the large amount of low quality lignite used in the largest Bulgarian thermal power plants. The tendency of a decrease of emissions in the last years of this period is related to the economic depression and the corresponding decrease of production; it is not due to the application of a new energy strategy aiming at fulfilling the requirements of the protocols signed and of other international agreements concerning these emissions.

2.4. The ENPEP model

This section summarizes the outcome of contacts and discussions with researchers at the Bulgarian Committee of Energy (ENERGOPROEKT) and the National Electric Company (NEK) regarding the application of the ENPEP model in Bulgaria. Only one of the ENPEP modules, the Electric System Expansion Planning module (WASP-3 software), is being fully adopted and applied in practice.

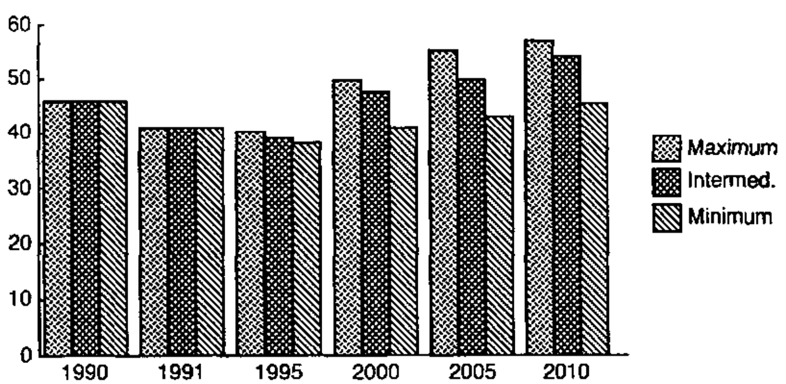

FIG. 3. Forecast of the electricity generation in Bulgaria up to the year 2010 (10^9 kW·h).

The PC version of this module is being integrated into the NEK operating system for development of forecasts. In combination with another powerful tool — the Integrated Resources Planning-Manager — the WASP-3 model is now being used as the basic tool in the NEK planning activities [7]. As an illustration, Fig. 3 shows the anticipated development of electricity generation in Bulgaria according to maximum, intermediate and minimum forecasts including environmental and least-cost considerations.

3. MAIN RESULTS

The main results of research carried out in the framework of the BCS are summarized below.

(a) Realization of the principal analysis of the Bulgarian energy system and in particular the electricity generation options.

(b) Development of a scheme for environmental impact analysis of the energy chains and the application of this scheme in a principal analysis of the thermal, nuclear and hydro energy chains in Bulgaria. The results of this analysis are presented in Tables III–V. The main types of environmental impact — emissions into air and water, land requirements, waste disposal — are divided into categories specific for each energy chain. The whole chains are considered, i.e. all levels in the process of electricity generation, and the specific environmental categories are ordered by level. If necessary, the categories are divided into more detailed sub-categories. In Table V, the seven categories have the following sub-categories: I. land requirements: 1.1. the hydropower plant itself and 1.2. the related facilities (reservoirs, channels, etc.); II. changes in the landscape: 2.1. earthwork during construction and 2.2. recultivation during operation; III. hydrological changes: 3.1. disturbance of the runoff of the river, 3.2. changes in the sediment regime and 3.3. changes in the water composition; IV. microclimatic changes: 4.1. changes in the climatic factors and 4.2. changes in the climatic elements; V. geodynamic changes: 5.1. changes in the facility's own territory and 5.2. changes in the surrounding territories; VI. technogenic risk; and VII. generation of new eco-systems. The environmental impact is estimated by four rates: 0 — no impact, 1 — weak impact, 2 — considerable impact, and 3 — strong impact. In this way the scheme combines synthesizing and analysing approaches and permits comparative assessments of different energy sources (chains).

(c) Collection, checking and formation of data to be entered in the BCSDB following the structure of the RTDB software and the design of the BCSDB in EXCEL 5.0 form.

(d) Performance of experiments with the software of the CO2DB and the RAINS model using Bulgarian data in order to study the applicability of these tools to the BCS.

TABLE III. ENVIRONMENTAL IMPACT OF THERMAL (FOSSIL FUEL) ELECTRICITY GENERATION

Levels in the simplified energy chain	Emissions into air			Emissions into water	Land requirements	Changes to the landscape	Solid waste	Heat rejection	Microclimatic and mesoclimatic changes
	Dust	Gases	Others						
II. Coal mining	1	1	1	2	2	2	1	0	1
IV. Fuel processing	1	0	0	1	0	0	1	0	0
VI. Electricity generation	2	3	2	1	1	1	2	1–2	1–2
XI. Waste disposal	1	0	0	1	2	2	2	0	1–2

TABLE IV. ENVIRONMENTAL IMPACT OF NUCLEAR ENERGY GENERATION

	Emissions into air	Emissions into water	Soil pollution	Land require-ments	Heat rejection	Hydro-logical changes	Techno-genic risk
Normal operation	0–1	0–1	0–1	1	1	1	0–1
Radiation accident	1–2	1–2	1–2	2	2	1–2	1–2

TABLE V. ENVIRONMENTAL IMPACT OF HYDRO ENERGY GENERATION

Categories of environmental impact	I		II		III			IV		V		VI	VII
Type of power plant[a]	1.1	1.2	2.1	2.2	3.1	3.2	3.3	4.1	4.2	5.1	5.2		
A.1	1	0	1	1	1	0	1	1	0	0	0	1	0
A.2	1	2	2	2	2	1	1	1–2	1	0	1	1–2	1
B	1	2	2	2	2	2	2	1–2	1–2	2	1	1–2	2
C	1	3	3	3	3	3	3	2–3	2–3	3	1–2	3	2

[a] A.1 — Run-of-river hydropower plant (HPP) without equalizer;
A.2 — Run-of-river HPP with equalizer;
B — Pumped storage HPP;
C — Storage HPP.

4. CONCLUSIONS

The three progress reports on the research carried out so far in the framework of the BCS show that efforts have focused on conceptual and methodological matters, not so much on factual ones. Especially scarce are results on the development of scenarios. Nevertheless, interesting and useful results have been obtained.

The experience gained so far within the BCS is summarized as follows:

(1) It is advantageous to use computerized tools as much as possible to achieve the goals of the BCS/DECADES project. The usefulness of the combined application of the RTDB/CSDBs, the CO2DB, and the RAINS and ENPEP models for this purpose is evident.

(2) The analysis of the present situation in the Bulgarian electricity sector provides enough facts regarding its seriousness — in respect of both the related environmental impact and the economic problems due to the transition towards market economy.

(3) The projections (scenarios) for the future development of the Bulgarian energy system on the basis of the RAINS and ENPEP models provide the necessary basis for the design of an economically and environmentally compatible energy strategy for the country.

The main results and findings from the research performed within the BCS indicate that it has been realized in accordance with the overall scope and objectives of the DECADES project as well as the research programme adopted for the study. Therefore, this research can be considered as a positive contribution to achieving the relevant goals. The additional research regarding the application of the RAINS model in the framework of the BCS was also useful. Future research will focus on the practical utilization of recent results from the BCS in order to achieve more effective and productive planning and decision making regarding the energy sector in Bulgaria.

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ASSESSMENT OF THE POTENTIAL ROLE OF NUCLEAR AND OTHER OPTIONS FOR POWER GENERATION IN CROATIA

D. FERETIC, Z. TOMSIC, Z. SIMIC
Faculty of Electrical Engineering and Computing,
Department of Power Systems,
Zagreb, Croatia

Abstract

ASSESSMENT OF THE POTENTIAL ROLE OF NUCLEAR AND OTHER OPTIONS FOR POWER GENERATION IN CROATIA.

Croatia has joined the interregional DECADES project with the aim of learning the methods for comparative assessment of the environmental impact of various power plants and their fuel cycles. Various strategies and options for future power generation in Croatia are being studied. A country specific database for electricity generation was established. Later, front-end and back-end technology chains will be analysed. The DECADES software model is used to improve the abilities for comparative assessment of different energy chains for electricity generation and different electricity supply strategies in the process of planning and decision making for the electricity sector.

1. INTRODUCTION

The main incentive for Croatia to join the interregional DECADES project coordinated by the IAEA was the possibility of learning the methods for comparative assessment of the environmental impact of various power plants and their fuel cycles. Various strategies and options for future power generation in Croatia are being studied and we hope that the application of the methods used in DECADES to these studies will contribute to their quality.

The first task of the assessment was to establish a database for the present energy sector and power system in Croatia and fuel cycles in accordance with the data included in DECADES. Since this is the first time that such data were required in Croatia, many data are missing and numerous gaps will have to be filled in the future.

2. THE ECONOMY OF CROATIA

Croatia is situated in south-eastern Europe. The Croatian territory extends over 56 538 km^2 and there are about 4.76 million inhabitants. In 1992, Croatia was internationally recognized as an independent State.

In addition to the problems caused by the transition from a socialist economy to a market economy and by the disintegration of a single-State system into several States, the greatest burden Croatia is carrying is undoubtedly the long term consequences of the war on the development of the country. The total direct damage to the energy sector is estimated at US $642.1 million. The indirect damage to the power supply sector and the economy as a whole, which is due to the destruction of power supply facilities and the unstable conditions in Croatia, is far greater and cannot be estimated at present.

3. ENERGY PROFILE OF CROATIA

An adequate energy policy, which is an integral factor in the realization of the planned economic development of Croatia, is being implemented by two public enterprises, Hrvatska Elektroprivreda (Croatian Electric Power Supply) and INA-Industrija Nafte (INA-Petroleum). Of the total input of prime energy in 1993, 70.1% is from liquid fuel, 11.0% from gaseous fuel, 12.7% from hydropower, 6.1% from coal and 0.1% from firewood. At present, Croatia imports about 35–40% of its required energy. Hydroelectric power plants contribute approximately 42% to the total production of electric energy, thermal power plants 39% and nuclear power plants 19%. The basic energy development policy is supply of the necessary energy through application of modern technologies, taking into account economy and ecology.

During the last few years the events in Croatia have had an influence on the trends in the complex energy system. The gross domestic product, the total primary energy supply and the gross energy consumption decreased during the period from 1991 onwards.

4. FORECASTS OF FINAL ENERGY AND ELECTRICITY DEMAND IN CROATIA

The economic changes that have taken place in Croatia, i.e. the transition from a non-proprietary system to a proprietary system, from a State regulated economy to a market economy, are even more important than the political changes.

Since there are no official estimates of economic growth in Croatia, an estimate of the maximum possible economic development until the year 2010 was taken into account. For the estimate of the electricity demand, the expected economic restructuring under the existing transitional conditions was considered, as well as the development of the standard of living and the technical progress with regard to a more efficient use of energy and electricity.

The economic and political changes that have occurred in Croatia reflect the energy use in the past. A forecast of the development of the Croatian energy system should be based on:

- An analysis of the present energy supply system;
- The relationship between demand, supply, transmission and distribution of all types of energy;
- Energy policy objectives, i.e. secure energy supply, parity of energy types, promotion of domestic energy sources, enhancement of the efficiency of the existing energy supply, and environmental protection.

The following resources are available for electricity production: imported coal, natural gas, nuclear fuel and renewable energy sources (solar, wind, biomass, hydro and geothermal energy).

Possible future power plant types in Croatia are: combined cycle thermal power plants (gas turbine and steam turbine), cogeneration plants (large plants for public heating and small industrial cogeneration plants), nuclear power plants, power plants for municipal solid waste and industrial waste, small hydropower plants and wind power plants.

5. THE DECADES PROJECT

Electricity generation chains are presented in DECADES as multilevel structures. In the suggested chains there are 11 levels which cover the whole process of electricity generation, from fuel extraction to distribution of electricity. A country specific database (CSDB) was established for electricity generation (level 6). The main reason for this was that in this phase of project development it was easiest to meet level 6 requirements because of the availability of data. Later, front-end and back-end technology chains will have to be analysed.

Data for level 6 of the CSDB for energy sources and technologies were collected from questionnaires. These data included technical, economic and environmental parameters. Data acquisition for level 6 of the CSDB was completed recently.

5.1. DECPAC software package

For a comparative assessment of the economic and environmental aspects of different electricity generation options and strategies we are using the DECPAC integrated software package for electricity system analysis and expansion planning, which is part of the DECADES model and its supporting databases, the reference technology database (RTDB) and the CSDBs. Data for existing and candidate plants from the CSDB were used to establish fixed and variable systems that can be applied in comparative studies for various electricity expansion strategies.

6. ENVIRONMENTAL IMPACT OF ELECTRICITY GENERATION

For the assessment of different electricity generation options and strategies, special attention is paid to environmental impacts from electricity generation chains and systems, such as emissions into air, water and soil, residuals, and direct impacts such as land use. Analysis of potential environmental impacts aims at identifying and quantifying all environmental effects of different energy chains for electricity generation and at valuating the impacts. The environmental analysis module of DECPAC calculates emissions into the air (CO_2) and provides information on the land requirements for each process, energy chain and electricity system level; this information is used for optimization and selection of candidate plants that will satisfy the environmental protection goals and standards.

The DECADES software model is used to improve the abilities for comparative assessment of different energy chains for electricity generation and different electricity supply strategies in the process of planning and decision making for the electricity sector.

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ENVIRONMENTAL IMPACTS OF ELECTRICITY GENERATION OPTIONS AND STRATEGIES IN EGYPT

S.M. RASHAD*, M.A. SWIDAN**, F.H. HAMMAD*,
F. ABUO NEAMA**, N.N. EL GAWLI**, A.A. EMARA*

* Atomic Energy Authority

** Egyptian Electricity Authority

Cairo, Egypt

Abstract

ENVIRONMENTAL IMPACTS OF ELECTRICITY GENERATION OPTIONS AND STRATEGIES IN EGYPT.

In Egypt and in most of the developing countries the demand for energy is growing very fast. The paper discusses the current structure and production of energy in Egypt, particularly in the electricity sector, as well as the environmental impacts and implications. The study includes energy and electricity planning for the coming two decades. The total energy demand of Egypt was 34 Mtoe in 1994. The total installed capacity of the national power system was 12 600 MW in 1993/1994. This is the total rated existing capacity of 147 units, composed of 67 steam units, 50 gas turbines, 5 modules of combined cycle units and 25 hydroelectric units. The hydropower potential, which played a prominent role in electric energy production in the 1970s, with a contribution of 75%, has declined gradually to 20% in 1994. An objective evaluation of the impact of the Aswan High Dam, based on data for 25 years of operation, indicates that its overall impact was extremely positive, even though it has contributed to some environmental problems. These problems, however, are much less than those originally expected. The electricity generation expansion plan up to the year 2015 is based on the following assumptions of the shares of different plant types in the annual electric energy production: 8% hydropower plants, 10% plants using imported coal or imported hydropower, 77% natural gas/heavy oil fired plants and 5% plants using new and renewable energy sources. Efforts have been made to incorporate environmental protection issues in the overall planning of the energy sector. The Egyptian Environmental Affairs Authority, in collaboration with the United Nations Environment Programme, is conducting a study on greenhouse gas costing in Egypt and on possible scenarios for reducing CO_2 emissions. The negative impact on the environment can be significantly decreased by reducing the annual growth rate of electric energy generation by implementing energy conservation measures to achieve improvements in energy efficiency and by establishing a policy for supply and demand management.

1. INTRODUCTION

The impact of energy and electricity generation technologies on the environment and on health has caused widespread local, regional and global concern, particularly in recent years. Such impacts are related not only to accident situations but also to normal operation of power plants. Accidents such as that at Chernobyl and the Exxon Valdez accident, the effects of war, for example the oil fires in Kuwait, and routine emissions of CO_2, SO_x and NO_x are major factors in the global energy-environmental issue. This paper deals with Egypt's approach to sustainable energy development and to a long term environmentally acceptable energy strategy. Regional energy planning would create opportunities for Egypt and its neighbours, and enhance co-operation between countries, e.g. supply of natural gas in return for power exchange through interconnections of electrical networks [1].

2. ENERGY STRUCTURE

2.1. Primary energy

The total energy demand of Egypt has increased from about 130 PJ (3 Mtoe) in 1950 to about 677 PJ (16 Mtoe) in 1980 and to 1473 PJ (34 Mtoe) in 1994, with an average annual growth rate of 6.3% in the 1980s. Hydropower has played a significant role in supplying Egypt's energy needs in the 1970s, providing more than two thirds of the electricity demand. In the late 1980s the situation was completely reversed, with oil and gas providing more than two thirds of the electricity demand. The pattern of energy supply by source in Egypt in 1990 was roughly 52% from oil, 22% from natural gas, 15% from agricultural waste, 8% from hydropower, 3% from coal and less than 1% from firewood. The primary energy consumption by sector in Egypt in 1994 was: 3% by the petroleum sector, 34% by the power production sector, 20% by the industry, 10% by households and commercial enterprises, 14% by the transport sector, 15% by agriculture and 4% by other sectors [2]. The kinds of fuel used in the industrial sector in Egypt are as follows: natural gas 39.94%, heavy fuel oil 36.22%, coal 17.06%, solar power 5.2%, kerosene 0.99%, gasoline 0.51% and diesel 0.07%.

The proportional consumption of the different sectors was as follows: metallurgical sector 33.77%, chemical sector 29.2%, textile sector 16.84%, engineering sector 0.89%, mining sector 4.48% and food production sector 14.82%.

Egypt's interest in R&D for renewable energies began in the late 1950s. In 1980, a strategy for renewable energy was developed and incorporated as an integral element of national energy planning. According to projections of the late 1980s, the annual energy savings to be achieved with renewable energy technologies were expected to reach 0.3 Mtoe in 1995 and more than 3 Mtoe by the year 2005 [3].

2.2. Electricity

More than 100 years ago, electricity was introduced in Egypt. Over the period 1960–1994, the electric power system has expanded tremendously. Electric energy production increased from 1.9 TW·h in 1960 to 48.6 TW·h in 1993/1994, with an annual growth rate of 10.9%. Over the same period, the peak load increased from 372 MW to 7657 MW, with an average annual growth rate of 9.6%. However, the corresponding average annual growth rate during the last decade was only about 5.8%, and this is expected to taper off to less than 5% in the coming decade. The installed capacity was about 12 600 MW in 1993/1994. This is the total rated existing capacity of 147 units, composed of 67 steam units, 50 gas turbines, 5 modules of combined cycle units and 25 hydroelectric units. The hydropower potential, which played a prominent role in electric energy production in the 1970s, with a contribution of 75%, has declined gradually to 20% in 1994 and has been compensated by domestic natural gas, which provided 80% of the thermal electric energy production [4].

Table I shows the development of the total installed capacity, the peak load, and the thermal, hydro and total electricity generated over the period 1983–1994. The electric energy generated in Egypt, in Africa and worldwide increased from 7.43, 113 and 6142 TW·h in 1973 to 42.54, 324 and 11 630 TW·h in 1990 [5].

TABLE I. DATA ON ELECTRICITY DEVELOPMENT FOR THE PERIOD 1983–1994

Fiscal year	Generated electricity (million kW·h)			Peak load (MW)	Total installed capacity (MW)
	Thermal	Hydro	Total		
1983/1984	18 053.5	9 637.1	27 690.6	4 672	6 123
1984/1985	21 060.1	9 003.7	30 063.8	5 158	7 713
1985/1986	23 197.9	9 046.1	32 244	5 361	8 370
1986/1987	26 097	9 104.7	35 201.7	5 803	8 933
1987/1988	29 586	8 258.6	37 844.6	6 152	8 933
1988/1989	30 258.2	9 322.2	39 580.4	6 279	10 068
1989/1990	31 674.3	9 974.3	41 648.6	6 664	10 604.5
1990/1991	33 745.8	9 732.3	43 478.1	7 004	11 281.5
1991/1992	35 277.7	10 204	45 481.7	7 215	11 535.5
1992/1993	36 610.5	10 485.8	47 096.3	7 503	11 910.5
1993/1994	37 633.03	10 971.2	48 604.23	7 657	12 046.3

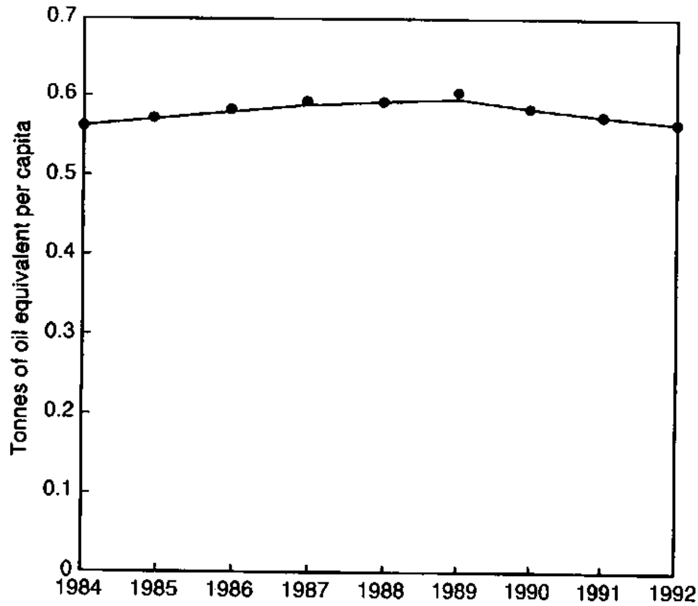

FIG. 1. Annual consumption of primary energy per capita in Egypt.

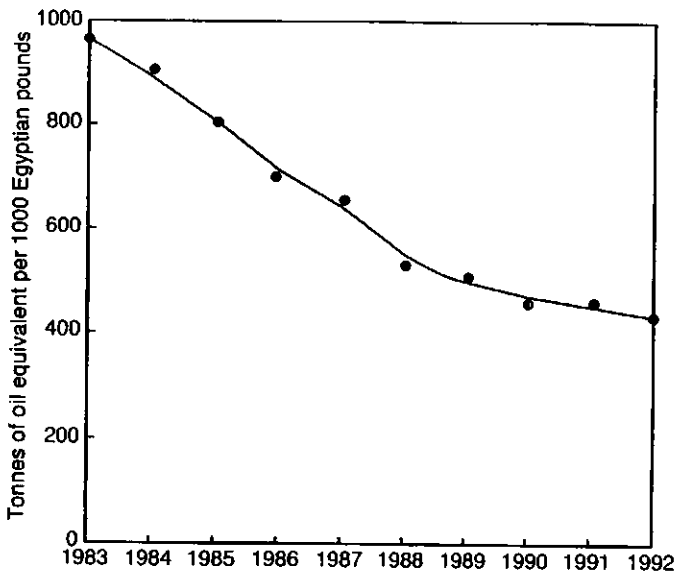

FIG. 2. Annual primary energy intensity.

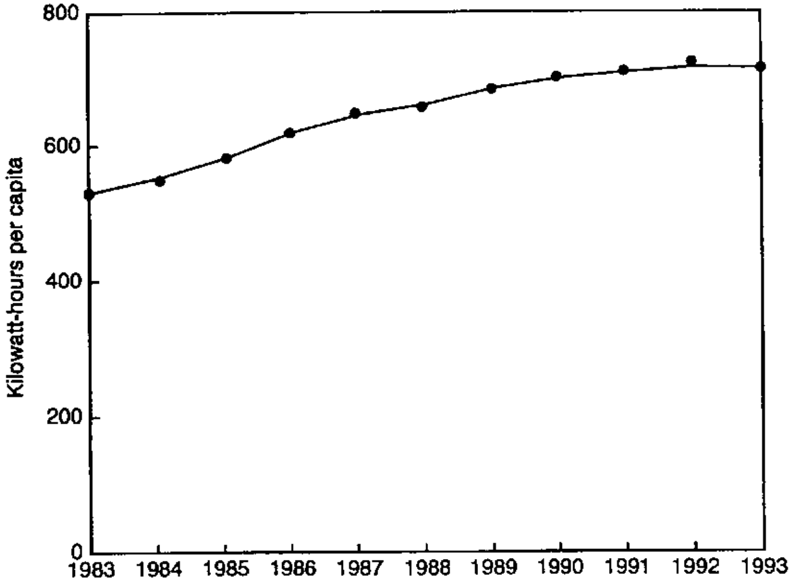

FIG. 3. Electricity consumption per capita.

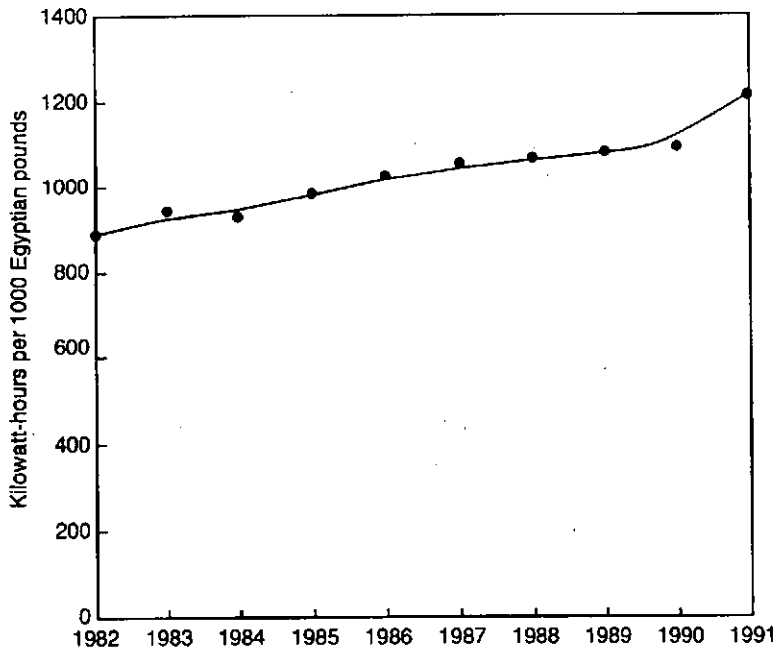

FIG. 4. Annual electricity intensity.

Regarding electricity consumption by sector over the last 14 years, the industrial consumption at different voltages played a dominant role. Next to this were the residential and commercial uses. During fiscal year 1994, about 46% of the total generation was used by the industry and 36% by the residential and commercial sectors.

2.3. Development of characteristic consumption and energy intensities

Figure 1 shows the annual consumption of primary energy per capita in Egypt (1984–1992). On the average, this value was 0.56 toe per capita per annum, which is about one sixth of that for some European countries [6]. If the energy consumption in Egypt is calculated per gross domestic product (GDP), as shown in Fig. 2, a decreasing trend is found, with the 1992 value being about 45% of the 1983 value. Regarding electricity consumption, the level per capita and the increase in consumption are even higher than those for total energy consumption (Fig. 3). In a previous study [6] the per capita consumption of the total energy generated and sold, and the per capita consumption excluding the industry were evaluated for the period 1980–1990. The per capita energy consumption in Egypt in 1988 was higher than the world average of 590 kW·h per capita per annum in other regions of the world (excluding OECD countries, the former Soviet Union and eastern Europe). Figure 4 shows the trend of the electricity intensity in Egypt from 1982 to 1991. The electricity consumption is calculated per GDP; the trend has been increasing from 886 kW·h/1000 Egyptian pounds in fiscal year 1983 to 1197 kW·h/1000 Egyptian pounds in fiscal year 1992.

3. EFFICIENCY OF ENERGY USE

3.1. Energy conservation and efficiency improvement programmes

Through the Organization for Energy Planning (OEP), Egypt has initiated national energy efficiency programmes at two levels [7]:

- At the national level: by conducting energy efficiency studies and programmes to identify topical areas that are common to several sectors, e.g. cogeneration, improvements in boiler efficiency, correction of the power factor.
- At the sectorial level: by initiating programmes for specific sub-sectors, e.g. metal industries, chemical industries, oil refining.

In the Egyptian petroleum refineries, special efforts were made and programmes applied with the aim of studying the energy required by the different processes and recommending measures and procedures for energy conservation.

TABLE II. ANNUAL AVERAGE FINAL PRODUCTS OF AN EGYPTIAN PETROLEUM REFINERY[a]

Type of product	Quantity produced (1000 t/a)	Percentage
Heavy fuel oil	782	49.3
Solar power	63	11.1
Gasoline	315	21.3
Kerosene	56	17.4
Butane gas	13	0.9

[a] Energy database of the OEP.

TABLE III. ANNUAL ENERGY CONSUMPTION OF AN EGYPTIAN PETROLEUM REFINERY

Type	Quantity	toe	Percentage
Electricity	15 130 MW·h	5 206	18
Heavy fuel oil	22 430 t	21 801	78.8
Gases	897 t	990	3.2

Table II shows the final products and Table III shows the energy required for the production processes of an Egyptian petroleum refinery. According to the data in Table III, about 0.0187 toe is required for the refining processes of 1 t crude oil. Some efforts were also made regarding the end use of electricity consumption. A programme was designed to promote the manufacture of energy efficient home appliances and to encourage consumers to use them.

3.2. Efficiency improvement in the electricity sector

Since the mid-1980s, a number of adequate measures were adopted by the electricity sector to maximize the generation efficiency. These include the use of combined cycle (CC) technology, the rehabilitation of some existing plants and the introduction of modern 300 MW units with better efficiency. In the framework of the rehabilitation programme, more than 280 MW have been added to the power system since 1989; the system is expected to reach 600 MW by the end of 1995. The accumulated savings in fuel consumption over nine years were about 15.138 Mtoe; this was achieved by reducing the average rate of fuel consumption from 331 g/kW·h in 1982/1983 to 229 g/kW·h in 1993/1994, based on gross electricity generation. In addition, the programmed economic dispatch operation of power system units according to their order of merit has led to considerable improvement in the overall efficiency.

In the last few years, effective measures have been undertaken to minimize transmission and distribution losses. This was achieved by installing the necessary capacitors at some transmission and distribution points, which resulted in a reduction of the line losses from 22% in 1981/1982 to 14.4% in 1990. Efforts are under way to achieve a reduction of about 12–14% by the end of the century. These steps have influenced the peak load growth rate, which decreased from 12% in 1981/1982 to about 6% in 1990. The energy prices in Egypt were roughly 25% of the international price level in 1986. Over the period 1986–1990, the energy and electricity prices increased considerably. It is planned to reach economic levels of energy prices by 1995; in the framework of the economic reform programme of the Government, the electricity tariff has reached almost 70% of the long range marginal cost [3].

4. POWER SYSTEM PLANNING

4.1. Generation expansion planning up to the year 2015

The Egyptian Electricity Authority (EEA), with the co-operation of international firms, has developed different load and energy forecasting methods and models, such as models to forecast the total energy sales, the energy generation and the peak load; and models to forecast the hourly energy demand and to provide load duration curves. In these models the classes of customers are classified as follows: very high voltage industry, high voltage industry, other industries, agriculture, public utilities; and residential, commercial and governmental services. The projected peak load and electricity demand will reach 19 400 MW and 126.5 TW·h, respectively, by the year 2015, with annual growth rates of 4.5% and 4.6%. The Electric Generation Expansion Analysis System (EGEAS) is determining the most economic way of generation expansion. The electricity generation expansion plan of the National Power System (NPS) up to the year 2015 is based on the assumption that the share of the different plant types in the annual electric energy production is as follows [4]: 8% hydropower plants, 10% plants using imported coal or imported hydropower, 77% natural gas/heavy oil fired plants, and 5% plants using new and renewable energy sources.

4.2. Prospects for electrical interconnection between Egypt and pan-Arabian and inter-African countries

The technico-economic advantages of electrical interconnections can be summarized as follows: reduction of investments for generation plants by providing pooling reserve; reduction of the unit investment cost by utilizing large units, thus benefiting from the economy of scale and gaining access to new techniques; reduction of the total operation costs of the interconnected system by using the most economic generating units; and reduction of the operation costs by decreasing the overall spinning reserve. The possible future interconnections between Egypt and other Arabian and African countries are summarized as follows:

— Egypt/Jordan/Syrian Arab Republic/Turkey,
— Egypt/Jordan/Saudi Arabia,
— Egypt/Libyan Arab Yamahiriya/Tunisia/Algeria/Morocco/Spain,
— Zaire/Central Africa/Sudan-Chad/Egypt.

5. ENVIRONMENTAL IMPROVEMENTS

Efforts have been made to incorporate environmental protection issues in the overall planning of the energy sector according to its national commitment and its technico-economic considerations. Energy efficiency improvements and development of the use of renewable energies are key elements in the measures adopted for environmental protection and greenhouse gas (GHG) abatement. The total emissions from commercial energy production in Egypt in 1991 are estimated at about 89 million t CO_2, 146 000 t SO_2 and 366 000 t NO_x, in addition to 19 700 t particulates. The following sections discuss the contribution of improvements in energy efficiency to environmental improvements, particularly regarding reduction of CO_2 emissions.

5.1. Energy consumption and GHG emissions

Table IV summarizes the energy consumption of the different sectors and the corresponding GHG emissions, mainly, but not exclusively, from activities in Egypt in 1990. The electricity generation sector and the industry and transport sectors are the major producers of CO_2. On the other hand, rice paddies are the main producers of CH_4; they are responsible for over 80% of the methane production in Egypt. Finally, nitrogen fertilizers and road transport are the main sources of nitrous oxide. The contribution of the power production sector to GHG emissions is less than its share in energy consumption because of the use of hydropower. The contribution of the petroleum industry to GHG emissions is higher than its share in energy consumption, mainly because of gas leakage. Table V shows the primary energy consumption

TABLE IV. SUMMARY OF GHG EMISSIONS IN EGYPT (1990)

Sector	Energy consumption (PJ)	CO_2 (Mt)	CH_4 (kt)	N_2O (kt)
Petroleum industry	43.50	3.10	51.9060	0.121
Power generation	464.63	24.75	0.0730	0.890
Heavy industry	144.41	18.81	0.0320	0.399
Light industry	138.59	9.30	0.0243	0.351
Household and commercial	134.57	9.34	2.6350	0.370
Transport	196.60	13.46	9.9340	7.091
Agriculture and domestic waste	212.12	0.67	424.2200	33.250
Others	58.82	4.08	1.1270	1.579
Total	1393.24	83.51	489.9513	44.051

TABLE V. PRIMARY ENERGY CONSUMPTION (PJ) BY SECTOR FOR THE BASE SCENARIO IN THE PERIOD 1990–2020

Sector	1990	2000	2010	2020
Petroleum industry	43.5	52.81	59.04	64.75
Power generation	464.3	711.37	993.23	1358.5
Heavy industry	144.41	227.23	322.52	468.86
Light industry	138.59	212.71	313.81	467.86
Household and commercial	134.57	208.97	299.43	367.9
Transport	196.6	241.92	285.43	314.17
Agriculture	212.12	281.71	350.63	420.56
Others	58.82	91.39	130.95	160.89
Total	1392.91	2028.11	2755.04	3623.49

by sector for the base scenario from 1990 to 2020. According to the estimation of GHG emissions, the sector emitting the largest amount of CO_2 is the heavy industry, although its share in energy consumption is much less than that of the power generation sector. The reason for this is that the CO_2 emissions in the cement and line industries are included in the heavy industry sector and that the power generation sector uses large amounts of natural gas.

5.2. Reductions of air emissions in the electricity sector

As mentioned in Section 4, the EEA has adopted measures for improving the energy efficiency in its plants and measures for reducing environmental impacts; for example, the EEA has increased the use of natural gas, which has the lowest impact on the environment. Recent improvements in gas turbine technology also contribute to making gas combustion more efficient. At present, natural gas represents 75% of the total fossil fuels used for thermal electricity generation in Egypt. Emissions of CO_2 from chmbustion of fossil fuels at Egyptian generating stations increased from 3.79 million t in 1967 to 20.2 million t in 1990. By using natural gas, emissions of about 4 million t CO_2 per year could be avoided. The CO_2 emissions from fossil fuels in the electricity sector are about one third of the total CO_2 emissions in the country. The per capita CO_2 emissions from the electricity sector alone were 0.12 t CO_2 per capita per annum in 1967 and reached an average value of 0.4 t CO_2 per capita per annum in the period 1990–1993 [6]. An objective evaluation of the impact of the Aswan High Dam, based on data for 25 years of operation, indicates that its overall impact was extremely positive, even though it has contributed to some environmental problems. These problems, however, are much less than those originally expected [8]. The continuous substitution of heavy fuel oil by natural gas in the 1980s as well as the improvements in supply efficiency have led to a considerable reduction of the gas emissions from the power plants of the EEA system. The estimated amounts of the main emissions reduced owing to energy rationalization measures of the power sector in 1991 are about 6.07 million t CO_2, 450 000 t SO_2 and 47 000 t NO_x [3].

Currently, the Egyptian Environmental Affairs Authority, in collaboration with the United Nations Environment Programme, is conducting a study on GHG costing in Egypt and on possible scenarios for reducing CO_2 emissions from the energy sector. Table VI shows preliminary projections of the effects of the abatement scenario up to the year 2020; it is predicted that the CO_2 emissions can be reduced by about 18% by the year 2005 and by 28% by the year 2020.

5.3. Reductions of air emissions in the industrial sector

Studies are being carried out to evaluate the global emissions from the industrial sector and to promote measures for reducing these emissions. The direct energy savings from the implementation of ECEP projects are expected to exceed 250 000 toe/a. This represents about 0.5% of the anticipated overall commercial energy demand in Egypt in 1995, and about 2.5% of the anticipated energy demand of the industrial manufacturing sector. This corresponds approximately to the following reductions in air pollutants: 800 750 t CO_2, 15 020 t SO_x and 3275 t NO_x.

TABLE VI. PROJECTIONS FOR ELECTRIC POWER GENERATION, FUEL CONSUMPTION AND CO_2 EMISSIONS (1990–2020)[a]

Year	BASE SCENARIO				ABATEMENT SCENARIO				Reduction (%)
	Generated electricity (GW·h/a)		Equiv. fuel oil	CO_2 emissions	Generated electricity (GW·h/a)		Equiv. fuel oil	CO_2 emissions	
	Total	Thermal	(1000 t/a)	(1000 t/a)	Total	Thermal	(1000 t/a)	(1000 t/a)	
1990	42 563	32 710	8 603	20 181	42 178	32 710	8 603	20 181	0.0
1995	56 656	46 021	11 643	27 156	55 072	45 462	11 502	26 753	1.5
2000	72 567	60 452	14 750	34 528	68 063	55 947	13 427	30 343	12
2005	92 617	78 442	18 826	44 515	84 092	69 258	16 276	36 406	18
2010	111 827	101 945	23 855	55 736	102 711	85 388	19 639	43 869	23
2020	174 979	153 580	35 323	89 225	148 732	121 265	26 678	63 798	283

[a] EEAA/UNEP greenhouse gas costing study of Egypt.

6. CONCLUSIONS

This paper has given an overview of the Egyptian targets, programmes and achievements in the area of energy and electricity planning, setting priorities for environmental improvements. The negative impact on the environment can be significantly decreased by reducing the annual growth rate of electric energy generation by implementing energy conservation measures to achieve improvements in energy efficiency, and by establishing a policy for supply and demand management.

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EXTERNAL COSTS OF THE NUCLEAR FUEL CYCLE

V. TORT, M. DREICER
Centre d'étude sur l'évaluation de la protection
dans le domaine nucléaire (CEPN),
Fontenay-aux-Roses, France

Abstract

EXTERNAL COSTS OF THE NUCLEAR FUEL CYCLE.

In the context of the Joule Programme of the European Commission (DG XII), the ExternE project has been implemented from 1991 to 1995 in order to assess the external costs of various fuel cycles used in the production of electricity. The Centre d'étude sur l'évaluation de la protection dans le domaine nucléaire has completed a study to evaluate the priority health and environmental impacts from the nuclear fuel cycle in order to estimate the external costs of each stage of the fuel cycle within a consistent methodological framework. Because of the large spatial and temporal range of the evaluation, the results have been presented in a time and space matrix to provide decision makers with the additional important information regarding the distribution of the external costs. In addition, to show the sensitivity of the final results to the use of a discount rate for the valuation of future impacts, a range of discount rates has been presented. In the course of this project, important issues have been identified for further work in order to improve the current methodology. Even though some unresolved issues remain, the study has made important advances in reporting the physical impacts and the monetary valuation of these impacts in a manner consistent with reporting impacts for other fuel cycles.

1. INTRODUCTION

As part of the European Commission (EC) DG XII ExternE Project on the Externalities of Fuel Cycles, the Centre d'étude sur l'évaluation de la protection dans le domaine nucléaire (CEPN) has completed a study on the external costs of the nuclear fuel cycle. The general objective of the study was to evaluate each stage of the French nuclear fuel cycle for a modern technology at a specific site, within the same framework as that for nine other fuel cycles included in the joint project to allow for direct comparison [1].

The nuclear fuel cycle in France was broken down into eight stages plus the transportation of material between the different facilities. The purpose of the evaluation was to estimate the priority impacts and to present a monetary value for these impacts. These priorities are related to public health in connection with environmental releases of radioactivity and occupational health. Although direct environmental impacts may occur, these have been shown not to be significant.

The routine first order upstream and downstream processes were considered for the whole fuel cycle. Moreover, in the case of electricity generation, the construction and decommissioning of a facility were considered. In addition, potential reactor and transportation accidents were also evaluated.

A key issue that has evolved in the course of this study was the distribution of impacts in a wide temporal and spatial range. The variation in the half-lives of radionuclides, the latency period between exposure and possible health effects, and the ability to calculate very small doses at large distances from the source make it possible to estimate impacts on a global basis and for thousands of years into the future. This distribution of impacts is an important input into the decision making process if direct comparisons between energy options are to be considered. The wide distribution of the impacts and the low level of individual risks that have been aggregated into significant figures have raised important questions as to the adequacy of the monetary valuation methodology for the assessment of the external costs of the nuclear fuel cycle.

2. METHODOLOGY

The general assessment methodology used in this study is referred to as the 'impact pathway approach'. A detailed explanation can be found in the main report of this project [2]. The impact pathway approach requires an inventory and an assessment of all potential impacts; however, in the context of the ExternE project it has not been possible to consider all of these. Therefore, only the most important impacts, called priority impacts, have been included. The priority pathways for the nuclear fuel cycle are based on:

- radioactive airborne releases,
- radioactive liquid releases,
- leakage from land based radioactive waste disposal,
- major releases from a reactor accident,
- occupational impacts,
- transportation impacts.

The sources of releases or direct impacts were identified for each facility and were used as the basis for estimating the resulting physical impacts. For each existing facility, representative annual rates of release to the atmosphere, into rivers and into the sea were determined for each radionuclide on the basis of past measurements or published data. Data for occupational accidents and exposures are based on actual measurements or published national statistics.

TABLE I. THE FRENCH NUCLEAR FUEL CYCLE

Stage of the fuel cycle	Site	Technology used
Mining and milling	Lodève	Underground and open pit mines, alkaline leaching
Conversion	Malvesi and Pierrelatte	Yellowcake conversion to UF_6
Enrichment	Pierrelatte	Gaseous diffusion
Fuel fabrication	Pierrelatte	Conversion of UF_6 to UO_2 pellets
Electricity generation	Belleville, Flamanville, Saint-Alban, Nogent, Paluel	1300 MW(e) PWR (pressurized water reactors)
Reprocessing	La Hague	PUREX process
Low and intermediate level waste disposal	Aube	Surface disposal
High level waste disposal	Auriat (hypothetical site)	Underground disposal
Transportation		Road and rail

Today, all stages of the nuclear fuel cycle are represented in France, except for a high level waste disposal repository. Therefore, for the assessment of the impacts of this stage, a hypothetical granite geological repository was considered. For the routine operation of the electricity generation stage, five different sites were evaluated in order to show the sensitivity of the results to the plant location. Table I presents the stages, sites and reference technologies that were considered in the assessment of routine operations for the French nuclear fuel cycle.

TABLE II. DISTRIBUTION OF IMPACTS FROM ROUTINE OPERATION OF THE NUCLEAR FUEL CYCLE IN TIME AND SPACE

	Local 0–100 km	Regional 100–1000 km	Global > 1000 km
Short term (< 1 year)	Non-radiological impact on workers Traffic accidents		
Medium term (1–100 years)	Radiological impact on workers and the public	Radiological impact on the public	^{85}Kr, ^{3}H ^{14}C, ^{129}I
Long term (100–100 000 years)	Radiological impact on the public	Radiological impact on the public	^{14}C, ^{129}I

Environmental models were used with a combination of site specific data (such as wind direction and speed, population distribution, agricultural production) and generalized European conditions (such as terrestrial transfer of radionuclides into agricultural products) to estimate the population exposures for the important radionuclide releases. Internationally accepted dose response functions specific to the radionuclides and modes of exposure (ingestion, inhalation, external exposure) were applied.

The definition of time and space categories was based on the type of models available and the need to compare the nuclear fuel cycle results with fossil fuel cycle assessments. Local and regional impacts, occurring in the short and medium term, were defined for the reference case. In addition, a specific evaluation was made in order to assess the long term and global impacts. Table II presents a breakdown of the time and space used for routine operation of the nuclear fuel cycle and the types of impacts included in each category.

Moreover, a probabilistic assessment was completed for the transportation risks and an indicative risk based evaluation was made for four possible severe reactor accident source terms.

The radiological health impacts for routine operations, and the number of potential fatal cancers, non-fatal cancers and severe hereditary effects in future generations were estimated using recommendations of the International Commission

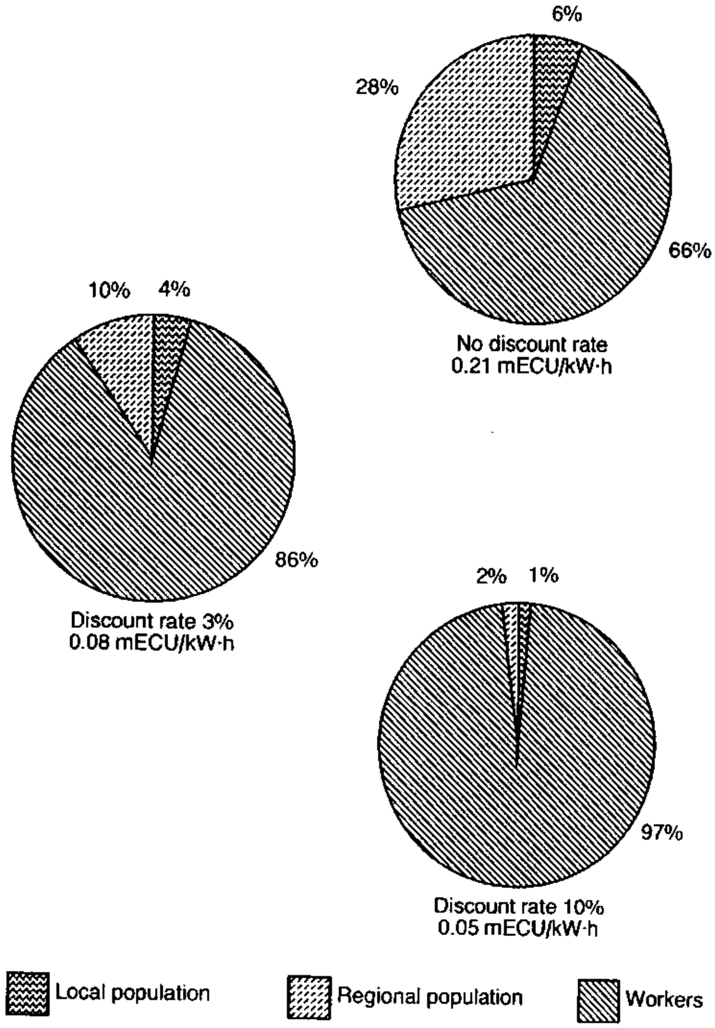

FIG. 1. Distribution of the costs for the different population categories for the assessment of the French nuclear fuel cycle for discount rates of 0%, 3% and 10% (routine operation, local and regional impacts, short and medium term).

on Radiological Protection [3]. The non-radiological impacts of accidental deaths and injuries on the general public, and the number of deaths, working days lost and permanent disabilities for the workers were based on published statistics. In accidental situations, additional effects of the immediate (deterministic) radiological impacts and the costs of radiation protection countermeasures were also calculated using the COSYMA code [4].

Whenever possible, the monetary valuation of these impacts was based on contingent valuation methods, in agreement with the whole EC project; however, at this phase of the project, estimated direct costs were used in some cases. For the valuation of deaths and severe hereditary effects, a common value of 2.6 MECU for a statistical life, based on contingent valuation studies, was used. A working day lost and permanent disability were considered to be the equivalent of 65 ECU and 19 kECU, respectively. These values are based on those used by the French national health insurance system. The value of 0.25 MECU for a non-fatal cancer is based on information on direct and indirect costs from the United States of America.

The costs were calculated with an annual discount rate of 3%; however, to understand the sensitivity of the results to the application of a discount rate, for valuing future impacts, the costs were also calculated without a discount rate, and with an annual discount rate of 10%.

3. RESULTS

For the reference case (routine operation, local and regional areas, short and medium term impacts and 3% discount rate), the sub-total of the cost for all stages of the nuclear fuel cycle is about 0.08 mECU/kW·h. This cost is dominated by the stages of mining and milling and reactor construction. When discount rates of 0% and 10% are used, the cost becomes 0.21 and 0.05 mECU/kW·h, respectively. The distribution of these costs for the different population categories for the three discount rates applied can be seen in Fig. 1, where the occupational impacts are largely dominant. These values can be compared with the current base load electricity generation costs in France of 35–40 mECU/kW·h.

4. DISCUSSION

4.1. Long term and global impacts

The major difficulty of the ExternE project from the methodological point of view concerns the evaluation of the external cost associated with the releases of radionuclides (^{3}H, ^{14}C, ^{129}I and ^{85}Kr) which have long term and global impacts because of their radioactive half-lives or their transfer into the environment. The external cost for these releases was estimated using models and hypotheses (migration into the environment, dose calculations, dose–response relationship, constant population, etc.) that have been internationally agreed but which are still being debated extensively.

Besides this modelling work, it is also important to set a space–time framework. A constant world population of 10 000 million people was adopted for the purposes of the evaluation; this figure was integrated over time for up to 100 000 years. Regardless of the radioelements and the period of time considered, the individual impact remains insignificant (maximum annual individual dose estimated to be in the range of 1×10^{-8} mSv/a). This global impact is largely due to the assessment of the impacts from ^{14}C, which is released from the reprocessing plant and from nuclear power plants. This value can be compared with the average individual dose of 1.2×10^{-2} mSv/a due to naturally occurring ^{14}C [5].

Integrating in space and time for the population as a whole, the global external cost increases by at most 10–20%. With a discount rate of 3%, the cost of global and long term impacts is 0.013 mECU/kW·h, which represents an increase of about 15% of the reference cost. The question could, however, be asked, whether, for the time-scales considered, the use of a discount rate of 3% remains valid. When no discount rate is used, this cost of long term and global impacts reaches 2.3 mECU/kW·h, and with a discount rate of 10% the increase in the basic cost is negligible.

4.2. Site sensitivity analysis

When no discount rate is used and when long term and global impacts are taken into account, the total costs of routine operation of electricity generation for each of the five reactor sites evaluated vary from 0.41 to 0.56 mECU/kW·h (0.44 mECU/kW·h on the average) and are dominated by the global impacts. If the external costs for construction and decommissioning are taken into account, this average value becomes 0.5 mECU/kW·h. In general, the regional costs for the sites located at the border of the sea (Flamanville, Paluel) are lower than those for the sites located on rivers (Nogent, Belleville, Saint-Alban).

4.3. Severe reactor accident

Calculation of the economic consequences of a severe reactor accident points out the difficult question of the choice of a reference scenario for the source term. To give an order of magnitude of the external cost of a hypothetical reactor accident, four potential release scenarios have been evaluated (0.01%, 0.1%, 1% and 10% of the core released), which cover the scenarios proposed within the ExternE project. The external cost has been derived with a simple aggregation of probabilities and consequences, without any further considerations of risk perception and the management of accidental risk. The range of costs from the assessments of a severe accident is 0.0005–0.023 mECU/kW·h for a conservative core melt probability of 1×10^{-5} per reactor and per year (based on a French assessment of a major core melt accident at a 1300 MW PWR reactor). The health impact costs are about 65% of the total cost for a massive containment release accident (10% of the core released) and about 80% of the total cost for a smaller accident (0.01% of the core released). One of the intermediate source terms, which corresponds to a release of about 1% of the core, is of the same order of magnitude as that for the reference accident scenario considered by the French national safety authorities. The estimated cost of this accident scenario is 0.005 mECU/kW·h. Although the portion of these costs that may be internalized by insurance against nuclear accidents has not been addressed, it should be noted that the cost of a potential accident does not significantly affect the total external cost.

5. CONCLUSIONS

In this comprehensive assessment of the French nuclear fuel cycle, site specific assessments of all stages of the fuel cycle have been made within a consistent methodological framework. According to the present developments of the calculation of the external costs, several key issues have to be further investigated:

(a) The validity of integrating very small individual exposures over large population groups and long time periods for the assessment of impacts;
(b) The global application of a monetary valuation methodology that has been developed for Europe;
(c) The use of discount rates for the assessment of costs for events very far into the future, such as leakage from waste repositories;
(d) The inclusion of public perception and risk aversion in the external costs;
(e) The determination of the portion of external costs that is already internalized; this would mainly concern occupational impacts.

Although the present study of the physical impacts of the nuclear fuel cycle is a comprehensive one, in presenting these costs it has been indicated that they are considered to be 'sub-total' costs and that they are not intended to represent the absolute total of the costs of all possible impacts. Within the constraints of the available resources and existing methodologies, the priority impact pathways have been analysed. In some cases, the assumptions have been pushed to the limit of validity in an effort to provide results that are as complete as possible.

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HEALTH RISKS OF ENERGY SYSTEMS

W. KREWITT, R. FRIEDRICH
Institut für Energiewirtschaft
und Rationelle Energieanwendung (IER),
Universität Stuttgart,
Stuttgart, Germany

Abstract

HEALTH RISKS OF ENERGY SYSTEMS.

Electricity generation from fossil, nuclear or renewable sources causes an increased level of ambient air concentration of pollutants or an increased level of ionizing radiation due to activities at the various process steps of the energy systems, resulting in adverse health effects on the general public. The results presented in the paper have been derived from a detailed impact pathway analysis, using air quality and dose effect models in a stepwise analysis of the chain of causal relationships, starting with the release of emissions from a power station through their interactions with the environment to a physical measure of impact. Public health impacts from increased levels of airborne pollutants due to fossil fuel electricity generation have been calculated using a set of air quality models and recently reviewed exposure response functions. Since airborne pollutants from renewable energy (photovoltaic, wind) systems are mainly emitted from upstream activities, a full life cycle analysis has been performed to capture major impacts. Public health risks from the nuclear energy system generally result from increased levels of ionizing radiation due to activities at various stages of the energy system. Since accidents are among the most controversial features of nuclear fuel cycle risk assessment, the paper focuses on the analysis of accident consequences using the COSYMA ACA package. The results show that the ranking of energy systems according to public risk depends strongly on the choice of the risk indicator. However, the general conclusion that can be drawn is that the risks resulting from the use of solid and liquid fossil fuels are at the upper end, while electricity generation from wind is an option with rather low risks per kilowatt-hour. A methodological framework, combining process analysis and input/output analysis, has been established to quantify occupational health risks from the full life cycle of the energy systems. To quantify the marginal risk induced by the choice of a specific technology, the concept of *net risk* has been introduced, taking into account only the difference between the risk of average industrial activities and the risk of the specific activity related to the fuel cycle of concern. Because of the high risk of underground mining, electricity production from coal has by far the highest occupational risks. Net risks from the photovoltaic system are negative, while occupational net risks from lignite, natural gas, wind and nuclear systems are positive but very low.

1. INTRODUCTION

Decisions on future technology choices have to reflect a wide range of economic, social, health and environmental aspects. Scientists from various disciplines are expected to provide aggregated information in support of the decision making process. The present paper summarizes the conceptual framework for quantification of health risks from fossil, renewable and nuclear energy systems. Following a detailed damage function approach, risk figures are derived for specific reference technologies, and the ranking of energy systems is discussed with regard to different risk indicators.

2. REFERENCE TECHNOLOGIES

Health effects resulting from electricity generation are expected to depend on the technical characteristics of the facility as well as on site specific meteorological conditions and demographic data. Results derived for a specific plant at a specific site should not necessarily be regarded as typical of any particular energy system. Tables I and II summarize some technical characteristics of the fossil fuelled reference power plants and of renewable energy systems. The nuclear energy reference

TABLE I. TECHNICAL CHARACTERISTICS OF THE FOSSIL FUELLED REFERENCE POWER PLANTS

	Hard coal	Lignite	Oil GT	Oil CC	Gas GT	Gas CC
Type	Dust fired, FGD, DENOX	Dust fired, FGD	Gas turbine	Combined cycle	Gas turbine	Combined cycle
Net capacity (MW)	600	589	155.9	527.9	145.7	777.5
Efficiency (%)	43	36.2	31.1	47	33.2	57.6
Full load hours (h/a)	6500	6500	675	6500	675	6500
Emissions (mg/kW·h)						
SO_2	570	655	1088	798	—	—
NO_x	570	655	822	798	577	208
TSP[a]	140	167	18	12	—	—

[a] Total suspended particles.

TABLE II. TECHNICAL CHARACTERISTICS OF THE WIND AND PHOTOVOLTAIC ENERGY SYSTEMS [7]

	Photovoltaic system	Wind system
Type	PV home application integrated into the grid, polycrystalline silicon modules	Windpark with 45 250 kW converters
Installed capacity	4.8 kW (peak)	11.25 MW
Annual electricity generation	3494 kW·h	24.3 GW·h
Technical lifetime	25 years	20 years

system is based on a modern 1300 MW pressurized water reactor (PWR); technical data describing the full energy system are taken from Refs [1, 2]. A more detailed description of the energy systems is given in Ref. [3].

3. PUBLIC HEALTH RISKS

3.1. Methodology

Electricity generation from fossil, nuclear or renewable sources causes an increased level of ambient air concentration of pollutants or an increased level of ionizing radiation due to activities at the various process steps of the energy systems, resulting in adverse health effects on the general public. The results presented here have been derived from a detailed impact pathway analysis, using air quality and dose effect models in a stepwise analysis of the chain of causal relationships, starting with the release of emissions from a power station through their interactions with the environment to a physical measure of impact.

3.1.1. Fossil energy systems

The incremental air pollution attributable to power generation is a mixture of the pollutants mainly emitted from the power station and those formed subsequently upon interaction of the emissions with the external environment. The air pollutants considered are particulates, SO_2, NO_x, ozone and aerosols.

Using no-threshold dose effect models, a simple conservation of matter argument led to the conclusion that the analysis needs to cover a range of up to several hundreds of kilometres in order to capture a major fraction of the total impact. Ambient air concentrations of primary pollutants on a local scale were assessed using a Gaussian plume model. The Windrose Trajectory Model (WTM), which was developed at IER on the basis of the Harwell Trajectory Model [4], was used to estimate the concentration and deposition of acid species on a regional range.

Health impacts from increased levels of airborne pollutants were calculated using a set of exposure response functions that was recently compiled by Hurley [5] on the basis of a comprehensive literature review. While direct impacts from SO_2 and NO_x are assumed to be negligible, health effects are dominated by secondary particulates (sulphate and nitrate aerosols) subsequently formed from gaseous SO_2 and NO_x emissions.

For the implementation of the impact assessment procedure, the computer system EcoSense has been developed and used at IER [6]. EcoSense is an integrated tool for environmental impact assessment, combining an extensive database on Europe-wide meteorological and receptor specific data with a set of air quality and dose effect models.

3.1.2. Renewable energy systems

In contrast to fossil systems, electricity generation from wind and photovoltaic (PV) systems does not cause any emissions at the generation stage. Instead, airborne pollutants are mainly emitted from material supply and component production activities, so that a full life cycle analysis is required to capture the major impacts. Emission data for the wind and PV energy life cycle were compiled in Ref. [7]. For impact assessment, emissions were assigned to specific industrial activities at typical locations and then used as input into the WTM mentioned above. The set of exposure response relationships derived for the analysis of fossil energy systems was also used to quantify the resulting health risks for renewable energy systems.

3.1.3. The nuclear energy system

Public health risks generally result from increased levels of ionizing radiation due to activities at various stages of the energy system. Risk figures for normal operation for the German reference plant were derived by using coefficients of normalized collective effective dose per unit activity released, from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [1], or by transferring results from a recent study published by the European Commission [2] to the German context. The resulting health effects were estimated using the extensively reviewed dose response functions of the International Commission on Radiological Protection (ICRP) [8].

TABLE III. FRACTION OF CORE INVENTORY RELEASED FOR SEVERAL ACCIDENT CATEGORIES[a]

Accident category	Fraction of core inventory released							Frequency of occurrence per year
	Noble gases	Iodines	Alkali metals	Tellurium group	Alkaline earth metals	Noble metals	Metal oxides	
DRSB 1	1		(0.5-0.9)		3.6×10^{-1}	1.0×10^{-5}	3.4×10^{-2}	10^{-7}
DRSB 2	1	3.7×10^{-1}	3.7×10^{-1}	2.3×10^{-1}	1.4×10^{-1}	2.5×10^{-6}	1.2×10^{-2}	10^{-7}
DRSB 3	1.7×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	5.0×10^{-2}	6.4×10^{-4}	8.8×10^{-8}	2.1×10^{-9}	10^{-8}
DRSB 4	1.7×10^{-1}	2.5×10^{-2}	2.5×10^{-2}	1.5×10^{-2}	1.2×10^{-4}	1.7×10^{-8}	3.8×10^{-10}	10^{-8}
DRSB 5	1	7.8×10^{-3}	7.8×10^{-3}	2.1×10^{-3}	1.4×10^{-4}	3.6×10^{-7}	1.1×10^{-5}	10^{-6}
DRSB 6	9×10^{-1}	2.0×10^{-3}	2.0×10^{-3}	3.5×10^{-6}	1.9×10^{-7}	6.4×10^{-10}	3.3×10^{-8}	10^{-6}

[a] According to the German Reactor Safety Study [9]; frequency of occurrence estimated on the basis of Ref. [10].

Accidents are among the most controversial features of nuclear fuel cycle risk assessment. The general methodology for accident consequence assessment is widely accepted and there exist several computer codes supporting the risk assessment procedure. However, the conditional link between source term and related probability of an event — certainly the major parameters determining the expected impact — remains a matter of controversial debate. For the present analysis, releases of radionuclides quantified for six accident categories of a 1300 MW PWR in the German reactor safety study Phase B [9] were linked to an estimated probability of accident [10] (Table III). To take into account site specific conditions, the reference plant was assumed to be located at a hypothetical site in the south-west of Germany. The computer code COSYMA [11] was used to calculate the resulting risks.

3.2. Results

Health risks resulting from the different energy systems vary considerably with respect to the temporal and spatial distribution of risks. The quantified risks from fossil and renewable systems are dominated by acute effects occurring on local and regional scales, while long term global effects mainly contribute to the overall risks from the nuclear energy system. When addressing issues such as inter- and intragenerational fairness and equity, the temporal and spatial distribution is an important parameter in the risk evaluation process that is not reflected in the expected value of risk. Economists use a discount rate to express preferences regarding a specific temporal distribution of events. However, there is a controversial debate on what is the 'right' discount rate. While environmental economists often suggest an empirically derived *social time preference rate* of around 2–4% for the valuation of environmental damage, many people argue for using a 0% discount rate, for ethical reasons. We use discount rates of 0 and 3% to illustrate the influence on the results.

Mortality risks per unit electricity generation are presented, using as indicators the number of deaths and the years of life lost. Almost certainly, acute mortality effects due to airborne particulates occur predominantly in older people with serious pre-existing ill health. The length of life lost is likely to be in the range of several days to a few weeks; for the present analysis we assume a reduction in life expectancy of 0.5 year. In contrast, the average loss of life expectancy due to a fatal cancer is 15.6 years [12].

For the wide range of morbidity end-points, ranking from, for example, a minor cough day to a non-fatal cancer, a common scale to be used for comparison is certainly needed. The concept of monetary valuation is used here to describe the relative weight of different health conditions. The monetary values used for the aggregation of mortality and morbidity end-points are summarized in Table IV. These values were derived from a comprehensive literature review and are discussed in more detail in Ref. [13].

TABLE IV. MONETARY VALUES OF DIFFERENT HEALTH END-POINTS [13]

Health effect	Monetary value (ECU)
Mortality (value of statistical life)	2 600 000
Respiratory hospital admission, including — Admission for respiratory infections — Admission for chronic obstructive pulmonary disease — Admission for asthma	6 600
Emergency room visit (ERV), including — ERV for chronic obstructive pulmonary disease — ERV for asthma — Hospital visit for childhood croup	186
Bronchitis	138.1
Restricted activity day	62.4
Asthma attack, including — Asthma attack — Shortness of breath day of asthmatics	31.3
Symptom day	6.3
Major occupational injury/disease	32 500
Minor occupational injury/disease	2 890

Taking into account the risk indicators discussed, Figs 1-3 summarize tl results from the risk assessment procedure. The risks from fossil energy systen using solid and liquid fuels are very similar; electricity generation from natural g is the option with the lowest risks from fossil systems. Discounting does not affe the results for fossil systems, as only acute impacts occurring at the time of electrici production are quantified. Discounting slightly increases the risks from PV and wi systems, as health impacts result from pollutants emitted during the constructi phase, i.e. before electricity generation. Since the quantified risks from the nucle energy system mainly affect future generations, the discounted risk is very sma The expected value of risk from a major nuclear accident is negligible compared the long term global impacts from routine operation. However, the potentially hi

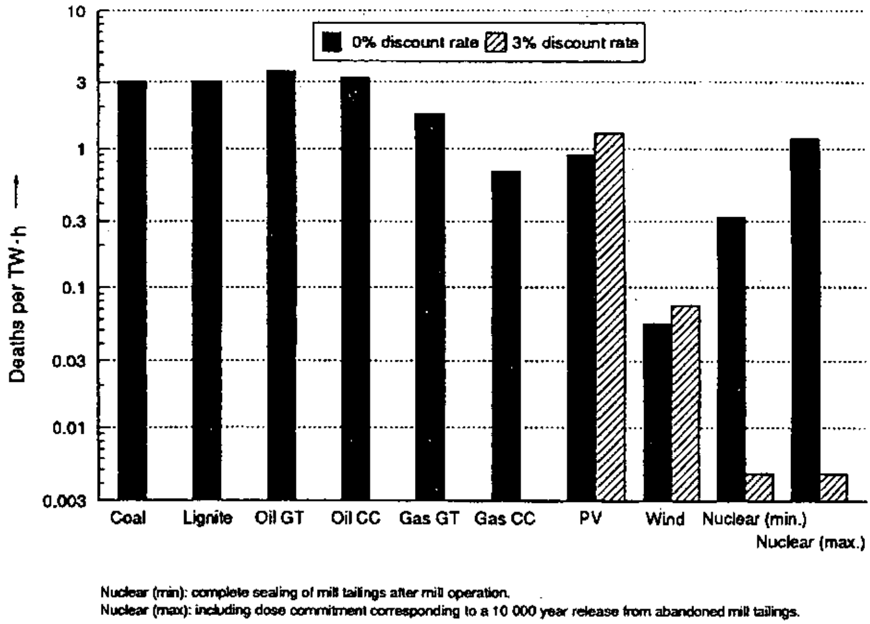

FIG. 1. Public mortality risks, expressed as number of deaths per TW·h.

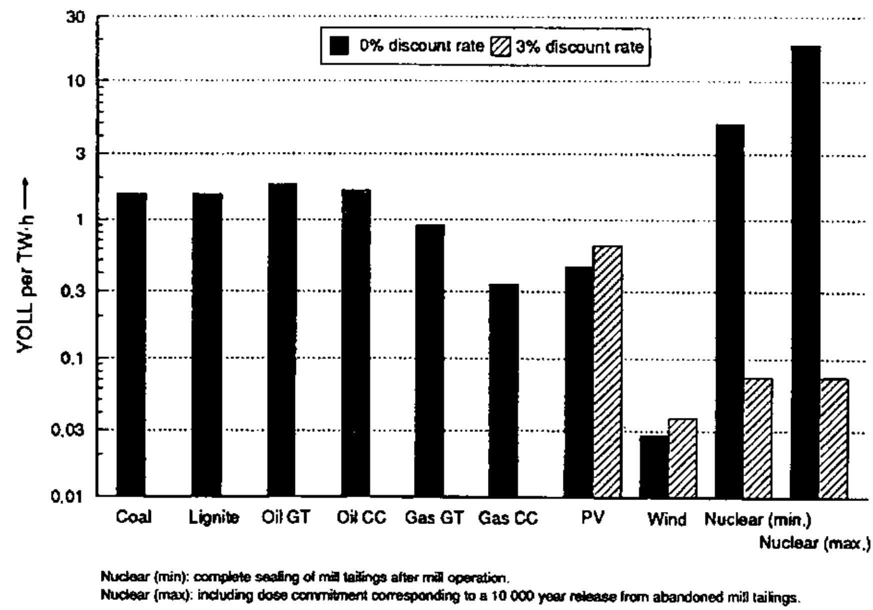

FIG. 2. Public mortality risks, expressed as years of life lost (YOLL) per TW·h.

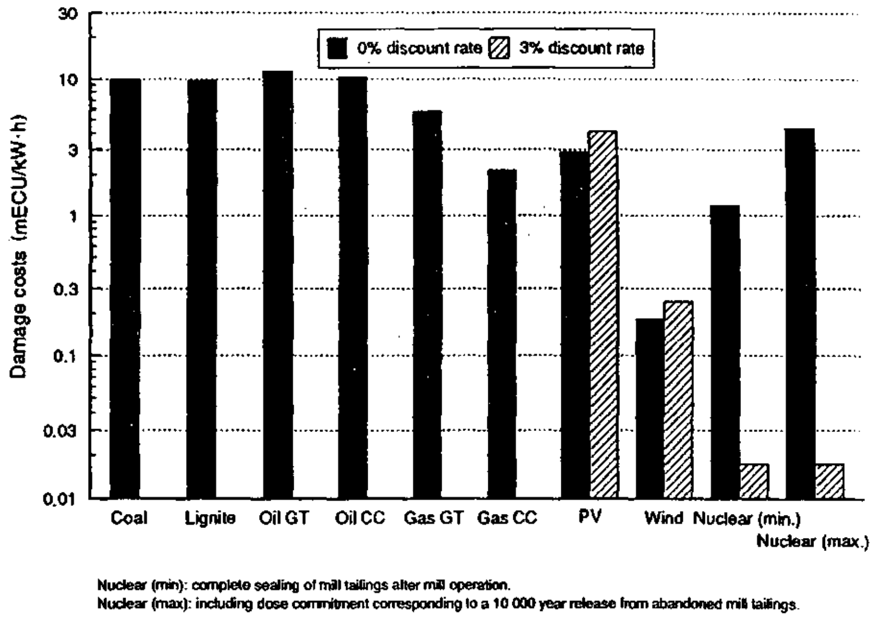

FIG. 3. Public mortality and morbidity risks, expressed as damage costs per kW·h.

damage from such an accident is an issue of major concern when taking into account risk aversion in the risk evaluation process. The use of either the number of fatalities or the loss of life expectancy as an indicator for mortality risks changes the ranking of energy systems significantly. Damage costs as an aggregated indicator of mortality and morbidity risks are dominated by the value of a statistical life, which does not take into account differences in reduction of life expectancy, so that the ranking of energy systems according to the damage cost indicator is similar to the ranking based on the number of fatalities.

4. OCCUPATIONAL HEALTH RISKS

4.1. Methodology

In contrast to public health impacts, occupational impacts are most easily assessed by evaluating occupational health statistics because of the closer relationship between cause and effect that is often found under specific working place conditions. In the case of diseases occurring after a long latency period, for example lung cancer from exposure to radon in underground mining, current data on health effects reflect the impacts of former exposure conditions. It is necessary to use exposure response functions to estimate impacts from today's exposure levels.

4.1.1. Evaluation of occupational health statistics

A methodological framework combining process analysis and input/output analysis was established to quantify health risks from the full life cycle of energy systems. Across all fuel cycles, for activities in the first order process chain (fuel extraction, transportation, electricity generation, waste disposal) a detailed process analysis was made. Input/output tables, extended by risk coefficients, normalized to a monetary unit turnover for each industrial sector, were used to calculate health risks from all upstream activities within the national economy [3]. Although in general the first order process steps are the major sources of risk, the mortality risk from upstream processes amounts to about 20% of the total risk from the coal energy system. For the nuclear energy system, only first order process steps were analysed because of lack of appropriate data for input/output analysis.

4.1.2. Application of exposure response functions

The risk of developing coal workers' pneumoconiosis was estimated by using a dose response relationship derived from surveys among British coal miners [14]. Lung cancer risk from underground exposure to radon was calculated using the Time Since Exposure Model of the US Committee on the Biological Effects of Ionizing Radiation [15]. The model is based on studies of uranium and iron ore miners. Health impacts resulting from occupational exposure to ionizing radiation at nuclear facilities were estimated using the ICRP 60 risk coefficients.

4.1.3. The concept of net risk

Since any occupational activity (and even leisure activities) causes positive health risks, the comparative risk assessment should only focus on the marginal (i.e. the additional) risk that is induced by the choice of a specific technology. For this purpose, the concept of *net risk* has been introduced, taking into account only the difference between the risk of average industrial activities and the risk of a specific activity related to the fuel cycle of concern. The concept of net risk has major implications for the comparison of impacts of different fuel cycles, in particular if work intensive technologies such as PV technologies are considered.

4.2. Results

Figure 4 summarizes occupational health risks per unit electricity generation from the different energy systems, using the damage cost indicator as an aggregated measure of mortality and morbidity risks. Because of the high risk of underground mining, electricity production from coal has by far the highest risks. Net risks from the PV system are negative, i.e. the work effort necessary for material supply and

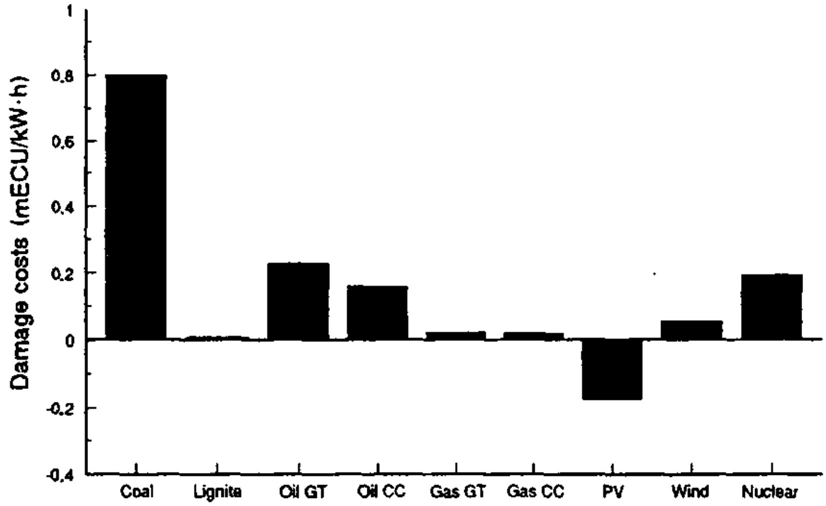

FIG. 4. Damage costs from occupational net risks.

component production for the PV system is from industrial sectors having risks lower than those of the average industrial activities. Occupational net risks from lignite, natural gas, wind and nuclear systems are positive but very low.

5. CONCLUSIONS

Public and occupational health risks from fossil, renewable and nuclear energy systems were assessed on the basis of a conceptual framework that was consistently applied across all energy systems. Public health impacts were calculated following a detailed damage function approach, using a set of air quality and recently reviewed dose effect models. The consequences of a major accident at a nuclear power plant were considered with regard to the expected value of risk. The results show that the ranking of energy systems according to public risk depends strongly on the choice of the risk indicator. However, the general conclusion that can be drawn is that the risks resulting from the use of solid and liquid fossil fuels are at the upper end, while electricity generation from wind is an option with rather low risks per kilowatt-hour.

To quantify occupational risks attributable to a specific energy system, the concept of net risk, taking into account risks induced by the choice of a specific technology, was introduced. The coal energy system clearly has the highest occupational risks, while the PV system is the only one characterized by a negative net risk.

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ENVIRONMENTAL IMPACTS ARISING FROM ELECTRICITY INTERCHANGES BETWEEN GREECE AND NEIGHBOURING COUNTRIES*

G.C. CONTAXIS, K. PERRAKIS, J. KABOURIS
Department of Electrical and Computer Engineering,
National Technical University of Athens

G. KORRES, S. VASSOS
Public Power Corporation

Athens, Greece

Abstract

ENVIRONMENTAL IMPACTS ARISING FROM ELECTRICITY INTERCHANGES BETWEEN GREECE AND NEIGHBOURING COUNTRIES.

The paper presents the results of a study dealing with an evaluation of the environmental impacts of electricity interchanges between Greece and neighbouring countries. Usually, the calculation of power interchanges between electricity generating systems is based solely on economic criteria; the environmental impacts of each system are not considered. Power interchanges affect the utilization of the individual generation systems and consequently the emissions from each system. It is anticipated that power interchanges have a different environmental impact for each system. The environmental impacts of emissions into the air (CO_2, SO_2, NO_x and particulates) from solid and liquid fuels are discussed. The study considers the interconnected systems of Greece and variants of the Italian and Bulgarian systems. The study is performed using two software packages developed at the National Technical University of Athens: PROSIM for probabilistic production simulation and POWEREX for evaluating the economy-energy interchanges between the power systems. Assuming no interchanges between the three systems, a detailed production simulation is performed for each system in order to calculate fuel consumption and the associated emissions for a period of one year. For the same period, the optimal interchanges between the three systems are then determined, with the objective of minimizing the overall production cost (pool operation). On the basis of these interchanges, the load demand of each system is adjusted and the detailed production simulation is repeated. The production costs and the emissions of the three systems with and without economy-energy interchanges are analysed.

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1. INTRODUCTION

Usually, exchanges of power between neighbouring systems are calculated on the basis of economic criteria, while the environmental impacts of each system are not considered. Power interchanges affect the utilization of the individual generation systems and consequently the emissions by each system. Therefore, it is anticipated that power interchanges have a different environmental impact for each generation system. The objective of this paper is to analyse the environmental impacts arising from interchanges of electricity between three neighbouring European utility systems; these impacts are calculated solely on the basis of economic criteria.

2. METHODOLOGY

The environmental impacts of emissions into the air (CO_2, SO_2, NO_x and particulates) from solid and liquid fuels have been studied. The interconnected systems considered in the study are those of Greece, and variants of the Italian and Bulgarian systems. The study has been performed using two software packages developed at the National Technical University of Athens (NTUA): PROSIM for probabilistic production simulation and POWEREX for evaluating the economic interchanges between the power systems.

The following methodology has been used: initially, no interchange between the three systems is assumed; detailed production simulation is performed for each system in order to calculate fuel consumption and the associated emissions for one year (1995). For the same year, the optimal interchanges between the three systems are determined, with the objective of minimizing the overall production cost (pool operation). Based on these interchanges, the load demand for each system is adjusted and the detailed production simulation is repeated. The production costs and the emissions of the three power systems with and without economic interchanges are analysed.

Concerning fuel prices, the prevailing international prices adjusted for transportation costs have been used in order to avoid distortion of the results due to differences in taxes, subsidies, etc., in the different countries and which should not be taken into account in the economic analysis.

The two software packages [1] used in this study are described in the Appendix.

3. DESCRIPTION OF THE THREE SYSTEMS

Data on the configuration and the operation of the three systems were collected and stored in appropriate databases, to be used subsequently by the simulation models (PROSIM and POWEREX). For the Greek generation system, the DECADES country specific database (CSDB) was utilized. The production of energy from renewable energy sources (hydro, geothermal) is described in Section 3.2 and information on the hourly loads of each system is given in Section 3.3. The connections between the three systems are described in Section 3.4. Finally, coefficients for emissions into the air due to the operation of the three systems were identified, several of them through the DECADES reference technology database (RTDB, [2]). The coefficients for each fuel type are given in Section 3.5.

The configuration and the operational data used for each system are not the actual ones utilized currently, but an appropriate approximation, fulfilling the requirements of the present study. A brief description of each system as represented in this study is given below.

3.1. Generation systems

Greece

The electricity generation system on the Greek mainland consists of thermal units (mostly lignite) and hydro units (mostly with a reservoir). The system of Crete and other autonomous island systems are not considered here. The net capacity of the Greek system in 1995 is shown in Table I.

TABLE I. ELECTRICITY GENERATION SYSTEM OF GREECE

	Net capacity (MW)	
Thermal units	5713	
Lignite		4533
Oil		1180
Hydro units	2514	
Run-of-river		8
With reservoir		2191
Pump storage		315
Total	8227	

TABLE II. ELECTRICITY GENERATION SYSTEM OF ITALY

	Net capacity (MW)	
Thermal units	34 923	
Oil		25 584
Coal		4 886
Natural gas		4 221
Lignite		232
Hydro units	19 600	
Run-of-river		5 400
With reservoir		11 000
Pump storage		3 200
Geothermal units	560	
Total	55 083	

TABLE III. ELECTRICITY GENERATION SYSTEM OF BULGARIA

	Net capacity (MW)	
Thermal units	8 545	
Nuclear		3 400
Lignite		2 105
Coal		2 000
Oil		650
Natural gas		390
Hydro units	2 032	
With reservoir		1 600
Pump storage		432
Total	10 577	

Italy

The Italian electricity generation system consists mainly of thermal units (mostly oil) and hydro units. Some geothermal capacity is also available. The net capacity of the Italian system considered for 1995 is shown in Table II.

Bulgaria

The Bulgarian electricity generation system presents a higher variety in terms of fuels used for electricity production, including significant nuclear capacity. The net capacity of the Bulgarian system considered for 1995 is shown in Table III.

3.2. Operation of hydro units

For each system, data for the prevailing hydro conditions and operation strategies have been collected. The hydro conditions assumed for 1995 are listed below.

Greece
- Run-of-river units, level of operation: 4 MW
- Reservoir units, expected energy: 3000 GW·h

Italy
- Run-of-river units, level of operation: 700–5000 MW, total energy: 42 000 GW·h
- Reservoir units, expected energy: 9500 GW·h

Bulgaria
- Reservoir units, expected energy: 1900 GW·h.

TABLE IV. ANNUAL ENERGY AND PEAK LOAD DEMANDS FOR THE THREE SYSTEMS

System	Annual energy (GW·h)	Peak load (MW)
Bulgaria (variant)	39 500	7 180
Greece	35 654	6 050
Italy (variant)	260 690	43 688

3.3. Load demand

For each electricity generation system the chronological load demand curves (8760 hourly loads) in 1995 have been estimated on the basis of a recent profile and forecasts of annual energy and annual peak load demands for 1995. The annual energy and peak load demands considered for each system are listed in Table IV.

3.4. Tie-lines

The following tie-lines have been assumed for the purpose of the present study:

Greece to Italy: 500 MW, which represents the capacity of the underwater cable to be constructed between the two countries.

Greece to Bulgaria: 400 MW, which represents the maximum capacity level at which the 1200 MW link is usually operated.

3.5. Environmental emissions

In order to calculate the environmental impacts from electricity generation, the following emissions from fossil fuel power generation plants are considered: CO_2, NO_x, SO_2 and dust. The emissions have been calculated using the respective coefficients for each fuel type. Average emission coefficients for each fuel type have been used, as shown in Table V.

TABLE V. AVERAGE EMISSION COEFFICIENTS PER FUEL TYPE (kg/MW·h)

Fuel	NO_x	CO_2	SO_2	Dust
Lignite 1 (Greece-Ptolemais, Italy, Bulgaria)	1.7	1229	0.9	1.4
Lignite 2 (Greece-Megalopoli)	1.6	1476	53.3	19.5
Coal	2.6	1050	7.8	0.78
Oil	1.20	943	14.9	1.6
Natural gas	1.0	180	0.01	0.01
Nuclear	0	0	0	0

4. RESULTS

4.1. Economy–energy interchanges

The energy interchanges resulting from the pool operation of the three electricity generation systems, calculated using the POWEREX model, are shown in Tables VI and VII. The total energy flows in each direction of the tie-lines are shown in Table VI and the accumulated energy interchanges between the three systems are shown in Table VII.

TABLE VI. TOTAL ENERGY FLOWS

Area 1	Area 2	Energy transactions from area 1 to area 2		Energy transactions from area 2 to area 1		Line utilization factor
		Energy (GW·h)	Hours	Energy (GW·h)	Hours	(%)
Bulgaria (variant)	Greece	3159	8368	52	326	91.91
Italy (variant)	Greece	764	2281	2954	6390	85.12

TABLE VII. ANNUAL ENERGY INTERCHANGES BETWEEN THE THREE SYSTEMS

	Exported energy (GW·h)	Imported energy (GW·h)
Greece	3006	3924
Bulgaria (variant)	3159	52
Italy (variant)	764	2954

4.2. Results of the production simulation

The results from the detailed probabilistic simulation of the operation of the three electricity generation systems, calculated using the PROSIM model, are shown in Tables VIII and IX. Table VIII presents the results for independent operation of each system. Table IX shows the results for each system after the load demand of each system has been modified according to the economy-energy interchanges obtained from POWEREX.

TABLE VIII. PRODUCTION SIMULATION BEFORE ECONOMY-ENERGY INTERCHANGES

	Generation (GW·h)	Unserved energy (GW·h)	Cost (US $1000)
Greece	32 476	144	903 368
Bulgaria (variant)	39 056	96	680 677
Italy (variant)	208 690	460	6 143 801
Total	280 222	700	7 727 846

TABLE IX. PRODUCTION SIMULATION AFTER ECONOMY-ENERGY INTERCHANGES

	Generation (GW·h)	Unserved energy (GW·h)	Cost (US $1000)
Greece	31 496	207	883 959
Bulgaria (variant)	42 056	203	740 524
Italy (variant)	206 738	221	6 094 988
Total	280 290	631	7 719 471

4.3. Environmental impacts

The environmental impacts (emissions from power generation into the air) resulting from the operation of the three electricity generation systems are shown in Tables X and XI. Table X presents the results for independent operation of each system. Table XI shows the results after the operation of each system has been modified according to the optimal economy-energy interchanges. Table XII shows the respective variations in per cent.

TABLE X. EMISSIONS INTO THE AIR BEFORE ECONOMY-ENERGY INTERCHANGES

	Generation (GW·h)	Emissions (t)			
		CO_2	NO_x	SO_2	Dust
Greece	32 476	41 793 040	35 717	328 215	337 779
Bulgaria (variant)	39 056	23 611 770	36 259	114 006	103 396
Italy (variant)	208 690	190 263 282	241 250	2 294 458	577 066
Total	280 222	255 668 092	313 226	2 736 679	1 018 241

TABLE XI. EMISSIONS INTO THE AIR AFTER ECONOMY-ENERGY INTERCHANGES

	Generation (GW·h)	Emissions (t)			
		CO_2	NO_x	SO_2	Dust
Greece	31 496	40 496 168	34 807	331 752	327 875
Bulgaria (variant)	42 056	26 837 018	40 990	130 546	118 018
Italy (variant)	206 738	188 558 325	238 938	2 267 685	574 356
Total	280 290	255 891 511	314 735	2 729 983	1 020 249

TABLE XII. VARIATION IN EMISSIONS INTO THE AIR AFTER ECONOMY-ENERGY INTERCHANGES

	Generation (%)	Emissions (%)			
		CO_2	NO_x	SO_2	Dust
Greece	−3.02	−3.10	−2.55	1.08	−2.93
Bulgaria (variant)	7.68	13.66	13.05	14.51	14.14
Italy (variant)	−0.94	−0.90	−0.96	−1.17	−0.47
Total	0.02	0.09	0.48	−0.24	0.20

5. CONCLUSIONS

The paper presents the initial results obtained from the analysis of the environmental impacts of energy exchange between neighbouring electricity systems for economic purposes. The results from independent operation of the three systems are also presented. It is pointed out that most emissions increase (decrease) at a higher rate than the respective increase (decrease) in the generated energy. Thus, in general, the increase or decrease of emissions does not lead to corresponding changes in generated energy. This is an important factor to be considered both in scheduling the economy-energy interchanges and in transmitting the resulting economic benefits.

Further analysis is under way, considering a longer time period and variations in parameters such as the capacity of the tie-lines and fuel prices, in order to fully assess the economic and environmental costs and benefits resulting from the interconnected operation of neighbouring utility systems.

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Appendix

POWER SYSTEM MODELS USED

POWEREX (power exchanges between interconnected systems)

POWEREX was developed in 1991–1993 at the Electric Power Systems Laboratory of the National Technical University of Athens under a contract with the Public Power Corporation of Greece. The model computes on an hourly basis the optimal energy interchanges (economy transactions) between interconnected power systems so as to minimize the total operating cost, taking into consideration the capacity limits of the interconnecting lines.

POWEREX also computes optimal interchange schedules between interconnected power systems for a period of several years through a chronological (hourly) simulation of the operation of the systems. The configuration of each system (generating units and tie-lines) is assumed to be known. In order to achieve maxium economic benefits, the generation systems are dispatched as a single composite system, without any transfer limitations between them. This operating mode results in the operation of the systems at a common incremental cost per hour.

The main simulation algorithm proceeds as follows: For each year the hourly load of each system is modified according to the energy generated by the non-dispatchable generating units (hydro, geothermal, wind). Then, a weekly maintenance schedule for the thermal units of each individual system is computed. The incremental cost curve for the current week for all systems is computed next. This is accomplished by ordering the available power blocks according to their incremental cost, taking also into account the forced outage rate of the thermal units via a 'pseudo-convolution' technique. On the basis of the incremental cost curves, a final modification of the hourly loads is performed in order to take into account the effect of the pumped storage units, which operate on an economic basis. Then, on an hourly basis, the operating point of each system is computed according to the equal incremental cost criterion. The tie-line flows are computed subsequently via a DC power flow, while any overloading is relieved by solving a linear program which minimizes the generation shifts from the optimum level.

The model uses hourly forecasts of the total load of each system. The system data include technical and economic data on plants, generating units, tie-lines and fuels used. Also, forecasts of the power and energy available from the non-dispatchable units are required.

PROSIM (production simulation model)

PROSIM simulates the operation of a power system for a given time horizon and computes the energy balance, the cost of operation, and the generation reliability (weekly, monthly and annually) in meeting the forecast load demand. Annual maintenance scheduling is automatically determined and the maturing process of the forced outage rate is modelled. The model allows timed step-wise unit rating as well as chronological changes in various solution options to be incorporated. The model also allows the production simulation to be performed weekly, or on four days of each week, representing Peak Day, Valley Day, Saturday and Sunday for the dispatch.

The model assumes that the chronological load curve and the parameters of the generation system (characteristics of thermal units, hydroelectric units and pump-storage units) are known. The simulation utilizes probabilistic techniques. Forced outage rates and maintenance requirements of generating units are taken into consideration.

In order to simulate the production, thermal units are modelled with up to four operating levels, with each level having an associated forced outage rate. Each capacity level is described by a two-state mode, i.e. it is either available or unavailable for generation at a given level when operation at that level is required.

On an annual basis, the model: (a) modifies the chronological load series to account for the operation of the hydro units; (b) constructs from the post-hydro chronological load series the load duration curve for each of the 52 weekly periods; (c) determines the annual maintenance scheduling based on the levelized reserve criterion; and (d) simulates the operation of the power system.

For each week, the model performs the following tasks:

- It determines the dispatch order of the blocks of the thermal units; the blocks are placed in a priority list in ascending order of their incremental cost or incorporated into the practices of the system.
- It dispatches the blocks of the thermal units according to the priority list. Probabilistic techniques are utilized to account for the forced outage rates of the units. The hours of operation and the required fuel for each thermal unit are determined.
- It dispatches pump storage units for compulsory and economic operation.
- It determines the reliability of the system in terms of the loss-of-load probability (LOLP).
- It determines the unserved energy.
- It determines the cost of operation.

PROSIM requires as input a load forecast time series, and the characteristics of the thermal units, the hydroelectric units and the pump-storage units.

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ASSESSMENT OF ALTERNATIVE ELECTRICITY SYSTEM EXPANSION STRATEGIES FOR HUNGARY

J. HOFFER
Computer and Automation Research Institute

P. DÖRFNER
Hungarian Power Companies Ltd

Budapest, Hungary

Abstract

ASSESSMENT OF ALTERNATIVE ELECTRICITY SYSTEM EXPANSION STRATEGIES FOR HUNGARY.

The paper describes the comparative analysis of different system expansion strategies under CO_2 emission limitations. In the framework of the DECADES project, the authors had the opportunity to test a new option of the alpha version of the WASP-IV model and computer tool on a real-life test problem concerning the Hungarian power system. The main technical characteristics of the existing power system in Hungary and of candidate units in the test case study, as well as their representation in the WASP model are discussed. The tasks in connection with the investigations of CO_2 emissions are discussed together with the results for the reference scenario and the expansion plans under different CO_2 emission limitations. The conclusions concerning the possibilities of CO_2 emission limitation for the Hungarian power system and the technical and organizational suggestions for the WASP-IV sofware package are summarized.

1. INTRODUCTION

The paper presents a comparative analysis of the different system expansion strategies for limiting CO_2 emissions. In the framework of the DECADES project, the authors had the opportunity to test a new option of the alpha version of the WASP-IV model and computer tool on a real-life test problem concerning the Hungarian power system.

Section 2 describes the main technical characteristics of the existing power system in Hungary and of candidate units considered in the test case study, as well as their representation in the WASP model.

Section 3 presents the different tasks in connection with the investigations of CO_2 emissions together with the results for the reference scenario and the expansion plans under different CO_2 emission limitations.

Section 4 summarizes the conclusions concerning the possibilities of CO_2 emission limitation for the Hungarian power system and the technical and organizational suggestions for the WASP-IV software package.

2. THE HUNGARIAN POWER SYSTEM

2.1. The existing power system

2.1.1. Installed capacity

The installed capacity of public power plants in Hungary was 7062 MW by the end of 1992. This is the total generating capacity of public power plants owned and operated by the Hungarian Power Companies Ltd. The break-down of this installed capacity on the basis of fuel type is as follows:

- 1840 MW in the nuclear power plant;
- 2087 MW in coal fired plants (including 800 MW capacity from lignite fired plants);
- 2885 MW in oil and gas fired plants (mainly alternatively);
- 202 MW in open cycle gas turbines;
- 48 MW in hydropower plants.

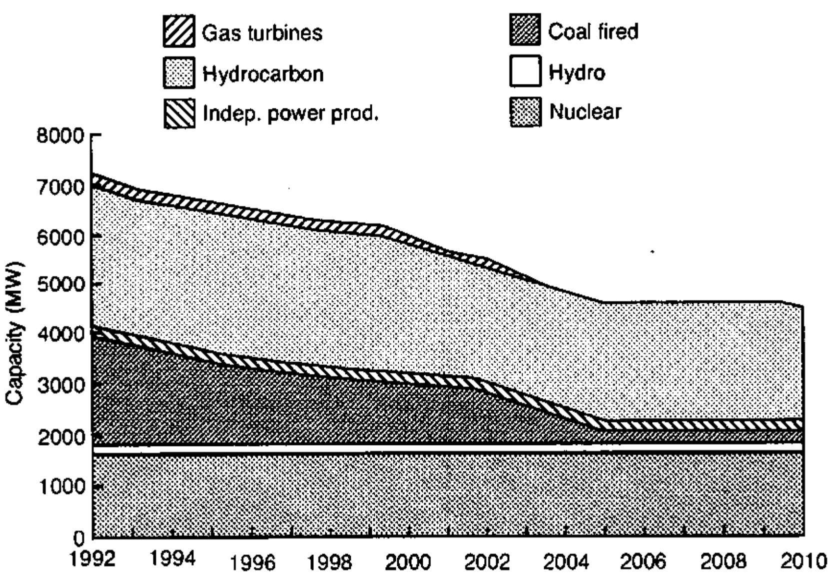

FIG. 1. Evolution of the capacities of the different power plant types.

Of the total steam power generation capacity of 4972 MW, 4470 MW is from condensation plants and 502 MW from cogeneration plants.

Most of the existing fossil fired plants are old. Of the fossil fired plants with a total capacity of 5174 MW, plants with a capacity of 2840 MW will be retired by the year 2010. Of the remaining plants with a total capacity of 2334 MW, ten 215 MW oil and gas fired units have a total installed capacity of 2150 MW; a capacity of 184 MW is from cogeneration.

The evolution of the capacities of the different power plant types is illustrated in Fig. 1. By the year 2010, the existing coal fired plants will be retired. However, after the year 2005, this scenario may be modified significantly owing to different circumstances. Retirement of nuclear units may become acute, for reasons of nuclear safety. Similarly, the retirement of oil and gas fired units will become urgent because of their deteriorating technical performance or their environmental impacts.

The installed capacity of hydropower plants is not expected to change over the study period. The existing 212 MW capacity of plants owned by independent power producers is relatively low. Significant changes are not expected to occur for this type of power generation.

2.1.2. *Electricity import*

In the Hungarian power system, import of electricity played a significant role in previous years. The contracted capacity of imported electricity was 1850 MW. The imported energy covered 28% of the gross domestic consumption. The transmission connections are strong in the eastern and northern directions, providing the opportunity of transporting significant amounts of electricity.

Recently, electricity import has dropped dramatically. The management of the Hungarian Power Companies Ltd intends to reduce the dependence on imported electricity, which means that the domestic demand will have to be satisfied mainly from domestic electricity generation. Electricity import may play a role if it is economic compared with domestic electricity generation; also, aspects of reliability of supply may lead to energy import in cases of emergency. Consequently, in our calculations, the net electricity import does not play a significant role; the expected import capacity is 120 MW per year, which is negligible compared with the amounts imported in the past and compared with the demand.

2.1.3. *Representation of different technologies in the WASP model*

For probabilistic simulation, the operation of the different electricity generation technologies has to be described in a proper way. The target of probabilistic simulation is the determination of power generation by each electricity generating unit for a given period of time, on the basis of the declared loading order. For these calculations, the technical and economic parameters of the generating units have to be known.

Two basic types of power generation technology can be differentiated in the modelling process and they are handled in different ways in probabilistic simulation. *Dispatchable units* can be stopped or operated on full capacity at any time. Condensation units and gas turbines are handled in this way.

Cogeneration units and hydropower plants can be dispatched only within certain limits. These units cannot be stopped at any time, and their available capacity depends on certain factors (e.g. heat demand for cogeneration, meteorological circumstances for hydropower). The electricity generation capability is not only determined by the installed capacity, but it also depends on different modifying factors. The latter units are called *non-dispatchable* or *fixed energy units* (*composite hydroelectric plants* in WASP terminology [1]).

The group of *dispatchable units* consists of

— Condensation steam units,
— Open cycle gas turbines,
— Nuclear units.

The group of *non-dispatchable units* consists of

— Hydropower units,
— Units with cogeneration.

Condensation steam units with significant cogeneration (e.g. combined cycle gas turbines) can be handled in two ways:

(1) The condensation and cogeneration parts can be represented separately in the calculations, even if they form physically one unit;
(2) The cogeneration part can be handled as the minimum capacity with the corresponding heat rate, and the condensation part determines the peak capacity and its incremental heat rate.

For the representation of combined cycle gas turbines, we have selected the second method in our calculations. Electricity generation of independent power producers and electricity import have been handled as non-dispatchable sources.

When dealing with power system expansion or generation planning, the fuel consumption and the CO_2 emission from the heat generation and the existing cogeneration must also be taken into consideration, even if they do not have a direct influence on the model calculations. For this purpose, fuel consumption and CO_2 emission will be calculated from the expected values of heat generation and cogeneration, and will be added to the results. Computation of these values is important, since in our investigation the overall CO_2 emission and fuel consumption of the power sector will be analysed. The evolution of the expected heat generation and cogeneration has an impact on the CO_2 limits in the model calculations.

TABLE I. TECHNICAL AND ECONOMIC PARAMETERS OF DISPATCHABLE UNITS

Name of power plant, fuel type	Number of units	Installed net unit capacity (MW)	Heat rate at full load (kJ/kW·h)	Forced outage rate (%)	Fuel cost (Ft/kJ)[a]
Dunamenti, oil	3	142	12 000	15.0	225
Dunamenti, oil	6	206	10 150	7.0	220
Mátra, lignite	2	90	14 500	20.0	205
Mátra, lignite	3	180	13 000	15.0	205
Tisza, gas	4	206	10 150	7.0	215
Tisza, coal	3	49	14 500	15.0	266
Oroszlány, coal	4	53	13 500	15.0	226
Bánhida, coal	1	93	12 000	15.0	212
Pécs, hard coal	2	53	13 200	15.0	260
Borsod, coal	2	26	15 500	15.0	222
Ajka, coal	2	26	16 500	15.0	220
Inota, coal	1	17	22 000	20.0	243
Inota, gas turbine	2	85	16 000	15.0	375
Kelenföld, gas turbine	1	32	16 000	15.0	375
Dunamenti, combined cycle	1	219	6 600	10.0	310
Paks, nuclear	4	432	11 600	4.0	50

[a] 100 Ft (1994) = 1 US $.

2.1.4. *Existing units in the model calculations*

The main technical and economic parameters of dispatchable units used in the calculations are presented in Table I.

2.2. Candidates for expansion of the power system

In the calculations, only dispatchable units are considered as candidates. Their main technical and economic data are summarized in Table II.

It is worth noting that the investment cost of the nuclear candidate is very high because it is the cost for units with advanced nuclear technology (not available commercially nowadays).

TABLE II. TECHNICAL AND ECONOMIC PARAMETERS OF CANDIDATE DISPATCHABLE UNITS

Fuel type	Number of units	Installed net unit capacity (MW)	Investment cost (million Ft/kW)[a]	Heat rate at full load (kJ/kW·h)	Forced outage rate (%)	Fuel cost (Ft/kJ)[a]
Imported coal	3	500	132	9 410	6.0	170
Lignite	1	528	180	9 188	9.0	200
Lignite	1	129	102	9 270	10.0	200
Nuclear	2	564	393	11 500	6.0	50
Oil	1	570	133	8 850	10.0	186
Oil	1	142	78	9 960	5.0	240
Fluid (imported coal)	3	132	118	9 160	6.0	190
Combined cycle gas turbine	3	200	78	5 450	4.0	310
Open cycle gas turbine	1	100	63	13 000	15.0	375

[a] 100 Ft (1994) = 1 US $.

2.3. Emissions of CO_2 from existing and new power generation units

For a power system, the CO_2 emission per unit electricity generated is an important factor. If the existing electricity generating units are heterogeneous regarding their CO_2 emission factors (i.e. the ratio of the amount of CO_2 emission to the electricity generated), then a proper tax system may have some potential for reduction of CO_2 emissions by changing the loading order. If these measures are not sufficient, then the differences between the CO_2 emission factors of the existing units and those of new units may provide a further opportunity to reach certain goals regarding mitigation of CO_2 emissions.

Tables III and IV give the CO_2 emission factors for typical existing thermal units and for typical thermal candidates in the Hungarian power system.

TABLE III. CO_2 EMISSION FACTORS FOR THE EXISTING THERMAL UNITS

Unit size (MW)	Fuel type	CO_2 emission factors (kg/kW·h)
180	Lignite	1.43
206	Oil	0.77
206	Gas	0.53
53	Coal	1.43
26	Coal	1.63
85	Diesel oil	1.17
219	Natural gas, combined cycle	0.36

TABLE IV. CO_2 EMISSION FACTORS FOR THE CANDIDATE UNITS

Unit size (MW)	Fuel type	CO_2 emission factors (kg/kW·h)
500	Imported coal	0.89
528	Lignite	1.01
129	Lignite	1.03
570	Oil	0.68
142	Oil	0.77
132	Imported coal	0.86
200	Combined cycle gas turbine (gas + oil)	0.37
100	Open cycle gas turbine (oil)	1.00

The differences in the CO_2 emission factors are significant for the different fuel types. Without application of scrubbers to remove the CO_2 output, the emission factors are significantly lower for hydrocarbon fired units, especially for natural gas fired combined cycle units, than for coal fired units.

3. INVESTIGATIONS OF CO_2 EMISSIONS AND RESULTS FOR THE REFERENCE SCENARIO

3.1. Description of the tasks

From a statistical analysis of emission data [2] it is clear that the power sector produces a significant amount of the CO_2 emissions in Hungary. In a first analysis step, the future CO_2 emissions from the power sector will be analysed, assuming that the least cost power system expansion plan is realized and that there is no significant intervention in order to decrease the emissions. The results obtained in this way will serve as the *reference scenario* for further analyses. Recently, two different demand scenarios were taken into consideration for the Hungarian power system. The present calculations will be carried out for the more realistic scenario with a lower energy demand.

In the next step, certain limitations to CO_2 emissions will be introduced into the least cost expansion problem. A constant limit on CO_2 emissions will be prescribed. The limits of the constraints on CO_2 emissions will be the CO_2 emission values obtained from the unconstrained production costing simulation for the year 1993.

In order to fulfil the CO_2 emission limits, modification of the power system expansion strategy will be allowed, but new expansion candidates will not be introduced. The technical and economic data of different candidates have been collected. In the near future, only these candidates will play a role, and no new candidates will be introduced to meet the CO_2 emission limitations. However, in a further step, some additional candidates will be chosen in order to investigate additional opportunities of reducing CO_2 emissions in the case of a better financial and economic situation.

Another important question is how the CO_2 emissions of the power system can be reduced by modifying only the loading order of power generating units in some selected years. The corresponding increase in the operation cost is also an interesting issue and therefore worth computing.

Our working hypothesis is that the existing power systems are not flexible enough for CO_2 mitigation, and there are much more opportunities for SO_2 emission abatement. This means that a considerable reduction of CO_2 emissions by changing the loading order cannot be expected.

3.2. Expansion plan without limitation of CO_2 emissions

For the reference demand scenario, the least cost expansion strategy is presented in Table V. The corresponding CO_2 emissions are illustrated in Fig. 2. By the year 2005, a large number of the existing inefficient coal fired plants will be retired. In the period 1995–2000, the investment programme is dominated by

TABLE V. EXPANSION STRATEGY FOR THE REFERENCE DEMAND SCENARIO (MW)

	Combined cycle	Gas turbine	Imported coal	Lignite	Oil	Nuclear
1995-2000	640	100	150	300	150	0
2001-2005	0	300	1800	0	0	0
2006-2010	0	200	150	0	600	0

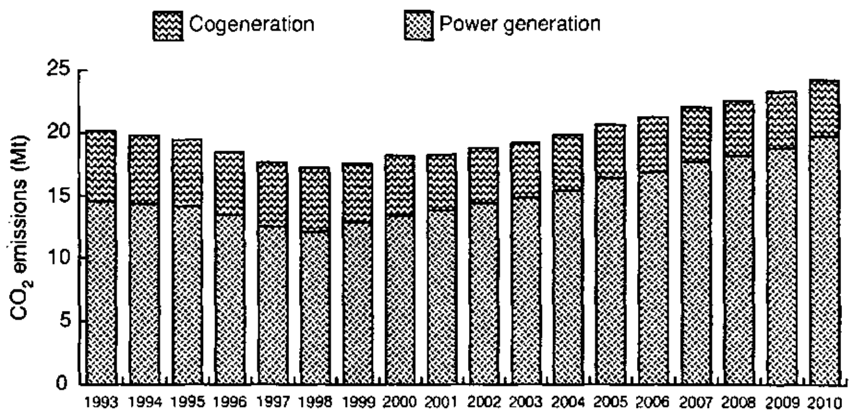

FIG. 2. CO_2 emissions for the reference scenario without limitations.

combined cycle units. Because of the efficiency improvements and the changes in the fuel structure, the CO_2 emissions will decrease in the first years of the study period, and there will be a slight increase from 1999 onwards. The emission level for the year 1993 is exceeded only after the year 2005. This means that up to 2005 there is no need for interventions in order to reduce CO_2 emissions.

The decrease in CO_2 emissions between 1993 and 2000 is an unexpected result. We will try to explain the reasons for this decrease. If we assume in the calculations that a generation of 1500 GW·h produced by coal fired units is replaced by the same generation produced by combined cycle gas turbines, then the corresponding decrease in CO_2 emissions is:

$$1500 \text{ GW·h} \times (1.43 \text{ kg/kW·h} - 0.36 \text{ kg/kW·h}) = 1.6 \text{ Mt}$$

The increase in demand is 1500 GW·h, which is partly covered by combined cycle units. The corresponding increase in CO_2 emissions is:

$$1500 \text{ GW·h} \times 0.36 \text{ kg/kW·h} = 0.5 \text{ Mt}$$

The net decrease in CO_2 emissions between 1993 and 2000 equals roughly 1.1 Mt, which is approximately the calculated difference (see first line of Table VI). This is actually a simplified calculation, but it is suitable to give a provisional explanation of the differences in CO_2 emissions between 1993 and 2000.

3.3. Reduction of CO_2 emissions by modification of the loading order

First we have calculated the evolution of the CO_2 emissions for the reference scenario. Then we have investigated the effect of loading order changes on CO_2 emissions. As mentioned above, no new investments have been considered in this analysis.

Three years of the study period have been selected, namely 1993, 1995 and 2000. The initial CO_2 emissions for these years are 20.1 Mt, 19.4 Mt and 18.1 Mt, respectively. The corresponding CO_2 emissions caused by the power generation considered in the model are 14.6 Mt, 14.2 Mt and 13.4 Mt. We have prescribed stricter limits for each year in order to see their effect on the CO_2 emissions and on the system reliability indices.

The WASP-IV methodology [3] distributes the annual environmental limits evenly over the periods of the year. However, the CO_2 emissions may vary significantly in different periods, following the evolution of the load characteristics and the corresponding thermal power generation. Consequently, if the CO_2 limit is set higher than the actual annual emission value, then new emission values for the periods and new annual emission values may be obtained.

Table VI lists the results of different WASP-IV runs, showing the annual CO_2 emissions and the loss of load probability (LOLP) values for different CO_2 limits.

The present algorithm of the WASP-IV prototype version uses a heuristic optimization method to fulfil the given group-limitations. As a consequence of the implemented methodology, unacceptable reliability indices may result. A really good solution would be direct control of the period LOLP values by leaving out strategies with high LOLP values. From Table VI it is clear that the opportunities for CO_2 emission reduction are extremely limited when only the loading order is changed.

From the computational results, the number of strategies (in the sense of WASP-IV [3] terminology) needed to meet the environmental limitations can be checked. For the most problematic periods, the number of strategies was extremely high compared with the average number of strategies in an SO_2 analysis. In the CO_2 analysis, the number of strategies increased to about 50 or 60, while in the SO_2 analysis the number of strategies was between 3 and 4. In addition, we observed that

TABLE VI. CO_2 EMISSIONS AND LOLP VALUES

Limit (Mt)	Annual CO_2 emission (Mt)	LOLP (%)	Annual CO_2 emission (Mt)	LOLP (%)	Annual CO_2 emission (Mt)	LOLP (%)
	1993		1995		2000	
16.0	14.6	0.382	14.2	0.946	13.4	0.789
15.5	14.4	0.408	14.2	0.946	13.4	0.789
15.0	14.4	0.408	14.0	0.946	13.4	0.789
14.5	14.1	1.235	13.9	1.362	13.4	0.789
14.0	13.7	1.235	13.7	1.362	13.2	0.789
13.5	13.5	3.839	13.5	3.937	13.2	1.004
13.0	12.9	6.447	13.0	5.659	12.6	2.052

small changes in the limitations might make a simple case problematic and difficult to solve.

In 1993, a reduction in CO_2 emissions by 0.9 Mt could be reached with loading order modifications that led to a still acceptable system reliability. For 1995, this value is 0.5 Mt, and for 2000 it is 0.2 Mt. The observed decrease in CO_2 emission mitigation is due to the different mix of generating units. In 1993, the old, inefficient units were still in operation, but, by the year 2000, most of them will be retired and replaced by more efficient and less carbon emitting units. Regarding the CO_2 emission factors in the system, their range for the year 1993 was wider than that for the year 2000.

The main conclusion of this investigation is that the opportunities of reducing CO_2 emissions by changing the loading order are extremely limited in the case of the Hungarian power system. In our analysis, the reduction achieved was between 1.5 and 6.0%. These low reduction values indicate that, without using mitigation technologies, the consequence of an increasing demand is an increase in CO_2 emissions. To reach significant results in regulating the CO_2 emissions, appropriate power generation technologies have to be introduced.

3.4. Constant limitation of CO_2 emissions

By introducing a limit of 20 Mt/a for CO_2 emissions, some changes were made in the investment programme. Table VII summarizes the least cost expansion strategy, taking into account the above CO_2 emission limitation.

TABLE VII. EXPANSION STRATEGY WITH LIMITATION OF CO_2 EMISSIONS (MW)

	Combined cycle	Gas turbine	Imported coal	Lignite	Oil	Nuclear
1995-2000	640	300	150	0	150	0
2001-2005	0	200	1800	0	600	0
2006-2010	0	100	0	0	0	1200

According to the calculations for the expansion strategy without limitation of CO_2 emissions (see Table V), changes are expected only in the last five years, since the emissions in the previous years did not exceed the given limit. However, the introduction of emission limitation may change the calculated amount of emissions also for previous years, even if the original emission value was lower than the limit. This is due to the concept of a homogeneous division of annual environmental limits into period limits used in WASP-IV. This phenomenon can be explained by the fact that at least one of the period limits may be exceeded by the corresponding period CO_2 emission value obtained by solving the simulation problem for unconstrained production costing (for further details, see Ref. [3]). This is the reason for the significant differences that will occur already by the year 2005.

Comparing Tables V and VII, the main changes in the investment programmes can be summarized as follows:

— All lignite fired units have been omitted from the expansion strategy;
— There is no need to introduce imported coal fired units after the year 2005;
— The introduction of oil fired units that was planned for the period 2006–2010 is planned for the period 2001–2005;
— Two expensive nuclear units have to be introduced at the end of the planning period.

From a practical point of view, the first three changes are acceptable, but the early introduction of advanced nuclear units is almost impossible, since it would cause severe and unacceptable financial problems. The economic situation of the country at that time is expected to be much better than the present one. Nevertheless, considering the long investment time, financial difficulties would arise before the year 2000.

There are additional problems as well. By the year 2006, i.e. just before the introduction of the first nuclear unit, the CO_2 limit will be too tight for the power system, in spite of the fact that the modified investment programme constitutes a power system that will emit less CO_2.

Since the existing power generating units have a certain structure, the opportunity for reduction of CO_2 emissions is extremely limited without introduction of new units that emit less CO_2. By the year 2006, the capacity balance is satisfactory and the reserve margin is acceptable in the reference investment programme. Problems are caused by the introduction of the emission limitation and the increasing demand. The result is an unacceptable level of system reliability by the year 2006. From this part of the analysis, some very important conclusions can be deduced and the subject of future investigations can be designated.

4. CONCLUSIONS

4.1. Opportunities for mitigation of CO_2 emissions

(a) Among the candidates for expansion of the Hungarian power system, the nuclear units are only feasible if the CO_2 limit represents a significant abatement of emissions. This will be the case after the retirement of the existing coal and lignite fired units and may also be a consequence of a demand growth rate that is higher than the one forecast.

(b) Introduction of special thermal units providing opportunities for CO_2 reduction is improbable in the time period investigated. Some typical electricity generation technologies for greenhouse gas mitigation are listed in the literature. Nevertheless, these technological solutions are not widely used worldwide. In Hungary, introduction of such commercial technologies cannot be expected, even if their investment and operation costs are not high.

(c) The potential for reduction of CO_2 emissions is extremely limited without the introduction of a new nuclear unit. Another opportunity for CO_2 reduction is the extension of the combined cycle programme, but this is a questionable solution because of the limited availability of natural gas for power generation.

(d) Introduction of CO_2 taxes for reduction of emissions could be successful if there were a sufficient potential for changes. In a first step, it will be necessary to find additional feasible expansion candidates that are able to ensure higher reduction rates of CO_2 emissions. It is not clear to what extent the introduction of such technologies is realistic.

(e) Before introducing CO_2 taxes, the possible effects of such a measure should be analysed. Further efforts are needed for a complete CO_2 tax analysis by running the present WASP-IV package for a large number of tax scenarios, since there is no explicit relation between the tax level and the CO_2 emission values. A detailed investigation could be the subject of a further study and could be performed if the project were continued. Nevertheless, it is possible that, if a very high environmental tax were introduced but if environmental constraints were omitted, the least cost expansion plan would not fulfil the environmental limitations because of the high emission factors of the present power generating units. If there were also nuclear candidates, the CO_2 taxes could be raised to such a high level that these candidates would become the cheapest ones and would represent the only option for satisfying the emission constraints. However, this solution cannot be realized in Hungary and it is therefore only a theoretical possibility.

(f) After performing tax level calculations, it is possible to determine a realistic goal to be reached by the management of the Hungarian power system. Hungary has to act together with other countries, but the system management has to realize the limits of the possible actions.

4.2. Modelling of environmental constraints

(a) The introduction of the 'multiple group-limitations' into the WASP methodology improves significantly the capabilities of the package for environmental modelling purposes.

(b) The complete introduction of this option into the original methodology should be completed as soon as possible (documentation, testing, etc.). The enhanced WASP version has to be tested by several experienced WASP users before dissemination of the package.

(c) The introduction of the 'multiple group-limitations' into the WASP methodology cannot solve the task of environmental analysis of power system expansion strategies. Nevertheless, it is possible to handle certain environmental constraints, but other environmental protection measures cannot be treated.

(d) The consistency of enhanced WASP and other ENPEP methodologies also has to be tested.

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RISK ASSESSMENT: THE NEED FOR EQUIVALENCE OF EVALUATION METHODOLOGIES

L. NOVIELLO
Nuclear Energy Division (ATN),
ENEL Società per Azioni,
Rome, Italy

Abstract

RISK ASSESSMENT: THE NEED FOR EQUIVALENCE OF EVALUATION METHODOLOGIES.

In the last twenty years, probabilistic risk assessment has been used more and more in the authorization process for hazardous installations. However, this mathematical tool did not always reach the intended goal of providing decision makers and the general public with adequate elements of the actual safety level of industrial installations. This is, in particular, the case with nuclear power plants. The consequences of an extreme use of the risk methodologies have become so evident over the years that today there is a strong case for regulators to return to common sense as a basis for regulation. The lack of an approach consistent with that used for other industrial hazards, that is the deviation from one of the most important bases of common sense — decision by comparison, has had dramatic consequences in terms of public acceptance and the cost of a kilowatt-hour. Regarding legislation in the European Union (EU), it can be seen very easily that, starting from the European Council Directive on the major accident hazards of 1982, there have been great efforts at the EU level and at the national level to more precisely define the methodologies for assessment and evaluation of industrial hazards. The author expresses his belief that it is time for nuclear energy to return to the common traditional path, as a way to obtain more balanced judgements.

1. INTRODUCTION

In the last twenty years, probabilistic risk assessment has been used more and more in the authorization process for hazardous installations. However, this mathematical tool has not always reached the intended goal of providing decision makers and the general public with adequate elements of the actual safety level of industrial installations. This is, in particular, the case with nuclear power plants. The consequences of an extreme use of risk methodologies have become so evident over the years that today there is a strong case for regulators to return to common sense as a basis for regulation. In my opinion and, as I have discovered recently, in the opinion of others [1, 2], the first step towards a return to common sense would be to identify common methodologies and rules for assessment of risks in all industrial installations independently of their type.

This is particularly important for electricity production. The electricity production market is becoming more and more a competitive market: plants that do not produce kilowatt-hours at competitive costs will be forced to shut down. There is nothing wrong with this, provided that all electricity sources have to demonstrate the same level of environmental and health protection, of course on the basis of common methodologies. In my opinion, today this is absolutely not the case for nuclear energy, which faces a number of handicaps:

— Sophisticated and unique methodologies are applied to nuclear energy;
— The consequences of accidents are evaluated with very conservative assumptions;
— Planning of emergency protective measures external to the site is required independently of the likelihood of a significant radioactivity release.

The lack of an approach consistent with that used for other industrial hazards, that is the deviation from one of the most important bases of common sense — decision by comparison, has had dramatic consequences in terms of public acceptance and the cost of a kilowatt-hour.

2. EXAMPLE OF DIVERSITY

The steps of risk analysis are broadly defined as follows:

— Identification of initiating events, their causes and mechanisms;
— Evaluation of the likelihood of occurrence of accidents;
— Evaluation of the consequences of each identified accident;
— Evaluation of risks.

Each of these steps involves a mix of assumptions, engineering judgement and analysis. The 'assumptions' are in most cases very delicate and somewhat arbitrary. Sometimes they are needed to bridge the gap in the scientific data and sometimes they are basically policy decisions which rest on value judgement; but if, for a specific hazard, all assumptions are made in a conservative way, starting from the concept "it is better to be safe than sorry", the end result is an evaluation of the related risks that may be extremely conservative.

The conservative approach could be acceptable, but only if evenly conservative assumptions and methodologies are applied to all energy sources. If this is not the case, then the differences in the conclusions may mislead the decision makers: an energy source can be put at a disadvantage against an alternative energy source just by the assumptions made.

In my opinion, nuclear energy is strongly penalized, at least in two major areas: the assumptions made in evaluating the consequences of accidents, and the range of events to be considered in the design. Regarding the first area, I would like to mention the fact that the most traditional design basis event, the loss of coolant accident (LOCA), would end up with negligible dose effects if it were evaluated with realistic methodologies, whereas it ends up with doses of tens of rems when it is evaluated with the conservative licensing methodologies.

The area I want to discuss more extensively includes the events to be considered in risk assessments: I believe that a few examples will help to better understand the problems that exist there.

One example refers to the envelope of initiating events taken into account. For a nuclear station, many initiating events that are not derived from plant equipment malfunction must be taken into account; for instance, it is required to evaluate the effects of seismic events of an intensity that is usually higher than that required by the building codes. As far as I know, nothing of this kind is required for gas fired plants. For consistency, the pipeline that supplies gas to the plant should be designed so that the supply to the furnace can be safely interrupted in the case of a seismic event. Of course, for the purpose of risk evaluation the pipeline should be seismically designed not only within the plant but also outside, at least up to the connection to the main national gas grid.

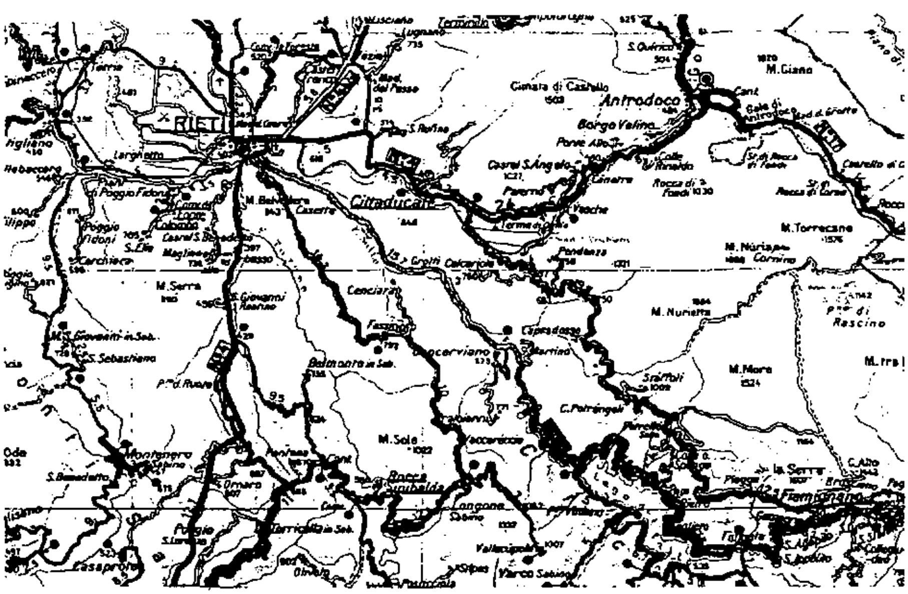

FIG.1. Example of an area with a quietly running hydroelectric power plant.

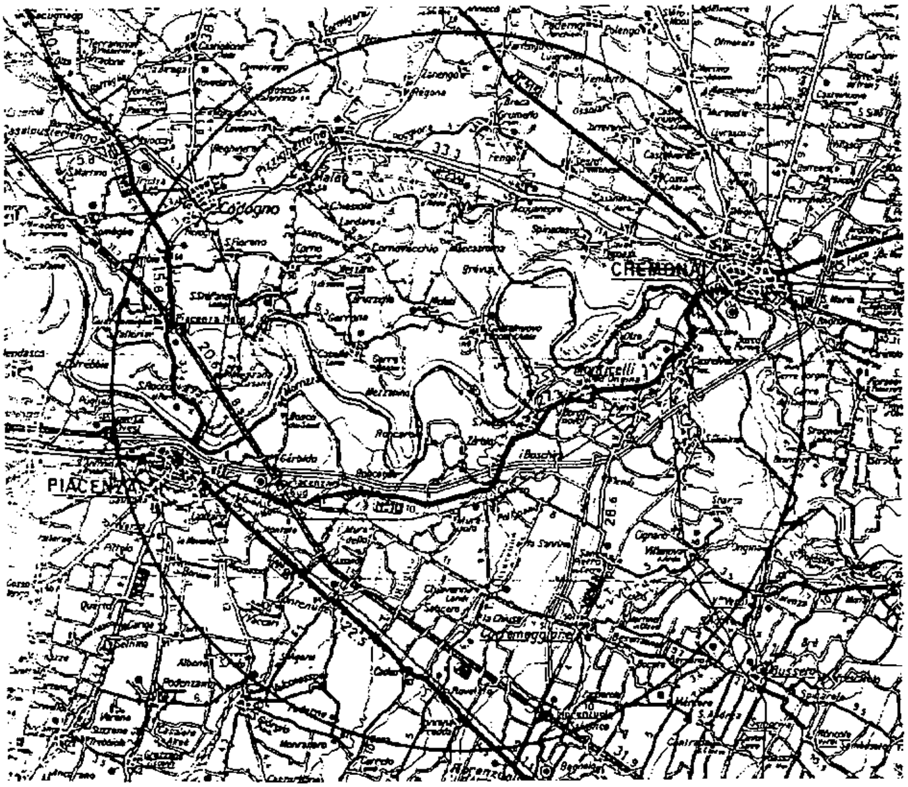

FIG. 2. Example of an area with a nuclear power plant that was shut down because it did not meet the EPZ requirements.

The second example, which is more useful for making recommendations, refers to hydro dams and to the way in which initiating events are selected for the design.

All countries with mountains use hydro dams to produce electricity. Of course, most of these dams are located in narrow valleys with high population densities, as in the case of the area shown in Fig. 1. Therefore, major consequences of a failure can be easily conceived. Nevertheless, the common situation is that the dams are accepted by the people and are even promoted by State laws as renewable energy sources. In my opinion, the explanation of this situation is the different design philosophy adopted for dams compared with that for nuclear plants. Actually, dams are designed on the basis of the traditional engineering approach that has evolved from thousands of years of experience. On the basis of their knowledge and of historical data for the likelihood of events, the engineers define the design basis and the related safety authorities review and approve it. Once the design basis is defined;

the dam is designed accordingly; if the need arises to discuss the safety of the dam, the approach is that events which are not included in the design basis are simply not considered. This approach may seem simplistic but, actually, it is the traditional approach to engineering and in the case of dams it is considered to be the only conceivable approach to their design.

If we look at this approach more closely, we may conclude that, after all, this is just one of the possible ways to apply the sophisticated 'risk assessment methodology' of the nuclear age. Actually, since the breach of a dam would almost unavoidably cause unacceptable consequences, the dam must be designed so that it does not break. Therefore, the design basis must include all conceivable accident scenarios. Since the engineers and the licensing authorities accept the responsibility of deciding which accident scenarios must be considered and which not, hydro stations gain ready acceptance.

This is not the case for nuclear plants; their design may be based on certain accident scenarios, while the risks may be evaluated on a different basis. The fact that for hypothetical extreme accident scenarios the analysis shows unacceptable consequences in most cases has not been enough either to include them in the design basis or to decide not to consider them at all, on the basis of a comparison with the average industrial risk to which the population may be exposed.

This inconsistency with the traditional engineering approach is usually perceived by the population as an ambiguity and, as a consequence, nuclear power has problems being accepted. Just try to imagine the attitude towards nuclear energy of the inhabitants of the area indicated by a circle in Fig. 2, who may have been told that the safety of the plant is very high, but, at the same time, that they might have to evacuate their houses suddenly. "The plant is safe, but please, just in case, be ready for a quick departure!"

3. TENDENCIES IN HAZARD MANAGEMENT LEGISLATION

Regarding legislation in the European Union (EU), it can be seen very easily that, starting from the European Council Directive on the major accident hazards of 1982, there have been efforts at the EU level and at the national level to more precisely define the methodologies for assessment and evaluation of industrial hazards.

The list of initiating events, the assumptions and the methodologies are being defined more precisely, and if we examine the regulations for the preparation of the risk assessments to be submitted to Governments, we do not find a philosophy that is very different from the one adopted for hydro dams. Accident scenarios with a frequency of more than 10^{-6} must be considered and the design has to be such that the consequences are limited to a radius of one or two kilometres around the installation. In other words, for an agreed design basis, defined with the best engineering judgement and possibly supported by probabilistic analysis, the environmental consequences must remain within deterministically defined limits.

4. THE RETURN OF NUCLEAR ENERGY TO THE TRADITIONAL ENGINEERING PATH

I believe that it is time for nuclear energy to return to the common traditional engineering path, as a way to obtain more balanced judgements.

One good reason for this is that the difference in approach has not helped the decision makers and the public to understand the actual level of safety of nuclear installations.

A second good reason for a return to the common traditional path is the simple fact that the sophisticated risk assessment approach used for nuclear energy is difficult to manage by the Government authorities responsible for emergency planning. As shown in Fig. 3, the emergency planning agencies need a reference

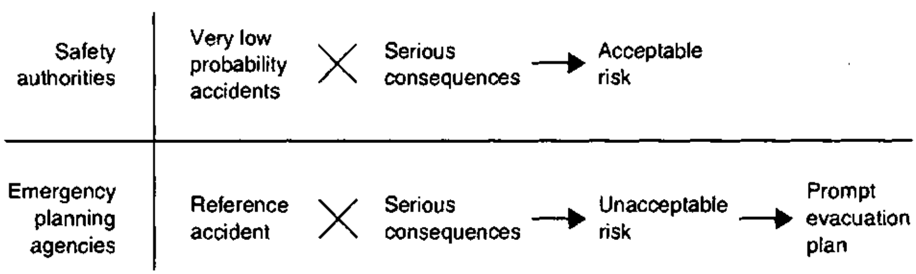

FIG. 3. Perception of the consequences of nuclear power plant accidents.

radioactivity release scenario to plan their actions. The fact that this scenario is very unlikely is meaningless for them: they have to take it as having probability one. On this basis they plan the protective actions, ask for facilities and devise regular drills.

As a result of the above, people living near nuclear plants who are not scared by what they have read about nuclear risk or what they have heard from opponents of nuclear power may be scared by the governmental authorities themselves.

The increase in knowledge in the field of severe accidents that occurred after TMI and the possibility to strengthen the containment of plants offer a golden opportunity to make a first step in returning to common sense, that is to establish consistent screening criteria for the identification of the accident scenarios to be considered in the design and to identify the performance required for the plants.

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ELECTRIC SYSTEM EXPANSION PLAN FOR THE REPUBLIC OF KOREA CONSIDERING CO_2 EMISSION CONTROL

Kidong SONG, Manki LEE
Korea Atomic Energy Research Institute,
Taejon, Republic of Korea

Abstract

ELECTRIC SYSTEM EXPANSION PLAN FOR THE REPUBLIC OF KOREA CONSIDERING CO_2 EMISSION CONTROL.

A study has been performed which evaluates the effect of a CO_2 emission regulation on the existing electric system expansion plan (ESEP) for the Republic of Korea. The study also estimates the proper rate of a carbon tax that may be levied on the electric power sector. A linear programming model has been developed both for planning and for estimation. Two scenarios concerning the level of CO_2 emission regulation have been studied. In the weak regulation scenario, stabilization of the CO_2 emissions by the year 2000 at the emission level of 1996 is assumed; in the strong regulation scenario, stabilization of the CO_2 emissions by the year 2000 at the emission level of 1992 is assumed. The results from the two scenarios are compared with the result from the reference case, for which no CO_2 emission regulation is assumed. It is suggested that, when the CO_2 emission regulation is imposed, the marginal cost of each energy source in the electric power system is the proper carbon tax rate. If the estimated marginal cost (carbon tax) were fully transferred to the fuel price, then the effect on the price of coal would be significant. The study suggests that the existing ESEP should be revised when the new regulation of CO_2 emissions is imposed on the electric system of the Republic of Korea.

1. INTRODUCTION

Because CO_2 emissions are supposed to be the principal cause of global warming, international regulation of CO_2 emissions is very important and several means of such a regulation have been discussed at an international level. When the Framework Convention on Climate Change became effective on 21 March 1994, the Republic of Korea, which had joined the Convention in 1993, had to fulfil the general rules imposed on developing countries. These rules are expected to be enforced at the level of developed countries, since the Republic of Korea is planning to join the OECD in 1996.

The electric power sector in the Republic of Korea accounts for a major portion of pollutant emissions. Its share of the total CO_2 emissions has continuously increased, from 14% in 1990 to 20% in 1994. This share is expected to be higher in the future because the demand for electricity is rising very fast. Therefore, the control of CO_2 emissions from the electric power sector plays a major role with respect to the reduction of the total CO_2 emissions in the country. Moreover, it is expected that, when the new regulation on CO_2 emissions becomes effective, a heavy burden will be placed on the electric power sector because it will be easy to control this public sector without impairing private economic activities.

The purpose of this study is to evaluate the effect of the CO_2 emission regulation on the existing electric system expansion plan (ESEP) for the period from 1994 to 2006. The study also estimates the proper rate of a possible carbon tax on the electricity generation sector in the Republic of Korea. The best way of evaluating the comprehensive impact of the CO_2 emission regulation on the electric power sector is to develop a macro-economic model which takes into account the feedback from various sectors. However, developing such a model is very costly and time consuming. Therefore, a linear programming model, which is easy to handle and can be used in the treatment of CO_2 emission control, has been developed. It is assumed that the CO_2 emission regulation is implemented only in the electric power sector.

The effect of internalization of externalities produced by CO_2 emissions is evaluated by assuming that the CO_2 emission regulation is internalized into the market mechanism by a carbon tax instead of direct control. The optimal rate of a carbon tax for the country's electric system is suggested in this study.

2. MODEL

The study is based on a linear programming model, which is similar to that developed in a previous study [1]. However, the present model is different from the previous one, in that it includes the following improvements:

- It is possible to implement the Integer Program in order to handle the indivisibility of electricity generating facilities;
- The O&M cost is explicitly taken into consideration in the objective function;
- The 'end-effect' is also treated in the objective function;
- Power plants to be decommissioned during the planning period are taken into consideration.

2.1. Objective function

The objective function is used to minimize the total discounted electric system costs, which are composed of capital cost, O&M cost and fuel cost.

2.1.1. Capital cost

The capital cost can be expressed as follows:

$$\text{Min.} \sum_j C_j X_j \qquad (1)$$

where C_j is the discounted capital cost of plant j (US \$/MW) and X_j is the installed electric capacity of plant j (MW).

The capital cost in the above objective function takes into consideration the 'end-effect' considered in this study. Previous studies have often neglected the 'end-effect' by assuming that the electricity demand beyond the planning period is zero. However, because this is a very unrealistic assumption, the results of such studies are usually biased towards introduction of a capital intensive plant near the end of the period. In order to reduce the bias, the model in this study implicitly assumes that the demand for electricity remains the same as that during the last year of the planning period.

In this study, the salvage value is taken into acount in the following manner. First, the total capital cost is converted to an annual capital cost. Next, if a plant's lifetime is within the planning period, the annual capital cost for the plant's lifetime is reconverted to the total capital cost. In this case, the two values are identical, implying that there is no 'end-effect' problem. However, if a plant's lifetime extends beyond the planning period, only the annual capital cost accrued up to the end of this period is reconverted to the total capital cost.

We define the capital recovery factor for the lifetime of plant j as CRFL T_j, and the capital recovery factor for this period from the introduction of plant j to the end of the period as CRFE T_j. Then the capital cost in the objective function can be modified as follows:

$$\text{Min.} \sum_j C_j X_j \, \text{CRFL } T_j / \text{CRFE } T_j \qquad (2)$$

2.1.2. O&M cost

The O&M cost is defined as the cost required to operate and maintain 1 kW of electricity generation for one month (US \$/kW·month). For the convenience of calculation, the total O&M cost of a plant for its lifetime is assumed to be used up at the time of introduction of the plant. Then, the total O&M cost of a plant for its lifetime is calculated simply by multiplying the inverse of the capital recovery factor with the O&M cost. However, some plants are decommissioned during the planning period. In this case, first the total O&M cost of all plants from the introduction period to the end period is calculated under the assumption that no plant is decommissioned during the planning period. Then, the O&M cost from the time of plant decommissioning to the end period are subtracted from the total O&M cost.

The O&M cost in the objective function can be expressed as follows:

$$\text{Min.} \sum_{j} (X_j \text{ OMCOS T}_j \text{ } 12/\text{CRFE T}_j)$$

$$- \sum_{i} \sum_{j} (\text{EX J}_{ij} \text{ OMCOS T}_j \text{ } 12/\text{EXJCR F}_i) \tag{3}$$

where OMCOS T_j is the O&M cost of plant j discounted to the reference year (US \$/kW·month), EX J_{ij} is the capacity of plant j to be decommissioned during period i, EXJCR F_i is the capital recovery factor for the beginning of period i (the period of decommissioning) to the end period, CRFE T_j is the capital recovery factor for the period from the introduction of a plant to the end period, and 12 is a factor used to convert the monetary terms from US \$/kW·month to US \$/kW·year.

2.1.3. *Fuel cost*

The fuel cost can be expressed as follows:

$$\text{Min.} \sum_{j} \sum_{i} \sum_{b} (F_{j,i} \, U_{j,i,b} \, q_{i,b}/(1 + DC)^i) \tag{4}$$

where $F_{j,i}$ is the fuel cost of plant j in period i (US \$/MW·h), $U_{j,i,b}$ is the power output of plant j at block b in the load duration curve in period i (MW), $q_{i,b}$ is the number of hours of demand block b in the load duration curve in period i, and DC is the discount rate.

2.1.4. *Objective function*

The objective function of the model in this study is as follows:

$$\text{Min.} \sum_{j} (C_j X_j \text{ CRFL T}_j/\text{CRFE T}_j)$$

$$+ \sum_{j} (X_j \text{ OMCOS T}_j \text{ } 12/\text{CRFE T}_j)$$

$$- \sum_{i} \sum_{j} (\text{EX J}_{ij} \text{ OMCOS T}_j \text{ } 12/\text{EXJCR F}_i)$$

$$+ \sum_{j} \sum_{i} \sum_{b} (F_{j,i} \, U_{j,i,b} \, q_{i,b}/(1 + DC)^i) \tag{5}$$

2.2. Constraints

The constraints are basically the same as those assumed in the previous study [1]; they include demand, plant output, existing plant capacity, reserve margin, hydropower and other factors. However, the CO_2 emission constraint is added in the present study. The implications of those constraints are briefly explained.

2.2.1. *CO_2 emission constraint*

The CO_2 emission constraint can be expressed as follows:

$$\sum_{j} \sum_{b} CO_2C\ F_j\ U_{j,i,b}\ q_{i,b} \leq CO_{2i} \text{ (for all i)} \tag{6}$$

where $CO_2C\ F_j$ is the CO_2 emission coefficient of plant j, and CO_{2i} is the level of regulation of the CO_2 emission in period i.

The CO_2 emission constraint implies that the annual total CO_2 emission does not exceed the level of regulation.

2.2.2. *Demand constraints*

$$\sum_{j=1} U_{j,i,b} \geq Q_{i,b} \text{ (for all i, b)} \tag{7}$$

where $Q_{i,b}$ is the demand level at block b in the load duration curve of period i. This constraint implies that the total output must be sufficient to meet the demand for electricity.

2.2.3. *Plant output constraint*

$$U_{j,i,b} \leq A_{j,i}\ X_j \text{ (for all j,i)} \tag{8}$$

where $A_{j,i}$ is the availability factor of plant j in period i. This constraint implies that the plant output does not exceed the net capacity of the plant.

2.2.4. *Existing plant capacity constraint*

$$X_j = \hat{X}_j \tag{9}$$

This implies that the installed electric capacity of existing plants is fixed and the existing plants are classified into 21 groups of similar types.

2.2.5. Reserve margin constraint

$$\sum_j X_j \geq Q_{i,b}\,(1 + m) \text{ (for all i, with b = 1)} \tag{10}$$

where m is the reserve margin. This constraint implies that the total capacity in period i must meet the peak demand and provide some allowance over the peak demand.

2.2.6. Hydropower plant constraint

$$\sum_j \sum_b L_j\, U_{j,i,b}\, q_{i,b} \leq H_i \text{ (for all i)} \tag{11}$$

where H_i is the maximum possible hydropower energy; L_j is 1 if the plant type is hydropower, otherwise L_j is 0. This constraint implies that the power from a hydroplant is limited by the water resources available to generate electricity and by the capacity of the plant.

2.2.7. Other constraints

The decommissioning schedule and the plants already committed under the Government's official ESEP are also reflected in the constraints.

3. INPUT DATA AND OTHER ASSUMPTIONS

The means for and the level of the international CO_2 emission regulation to be imposed on the Republic of Korea are not yet clear. However, since developed countries have already declared that their goal is to stabilize their total CO_2 emission by the year 2000 at the emission level of 1990, this study also assumes that the total quantity of CO_2 emissions will be fixed at a certain level by the year 2000. Also, since the Republic of Korea is still a developing country, it is assumed that a slightly milder regulation than that applied to developed countries will be applied to it.

Two scenarios have been assumed in the present study:

(1) the weak regulation scenario: stabilization of CO_2 emissions by the year 2000 at the emission level of 1996; and
(2) the strong regulation scenario: stabilization of CO_2 emissions by the year 2000 at the emission level of 1992.

The study assumes a Reference Case ESEP, which is the result of the linear programming model when only the CO_2 emission constraint is excluded. Since the Republic of Korea already has an official ESEP, fixed by the Government, covering the period until the year 2006, efforts are made for the Reference Case ESEP to be

TABLE I. GENERAL INPUT DATA OF THE MODEL

Reference year: price	Beginning of 1994
Reference year: discount rate	Beginning of 1994
Expenditure time: cost	End of each year
Discount rate	8%/year
Exchange rate	800 Won = 1 US $
Planning period	1994–2006
Lifetime of plants	
— Nuclear power plants	30 years
— Coal fired plants	30 years
— Liquefied natural gas (LNG) plants	20 years
— Hydropower plants	50 years

TABLE II. CAPITAL COST, O&M COST AND FUEL COST

	Capital cost (1000 Won/kW)	O&M cost (Won/kW·month)	Fuel cost (Won/kW·h)
Coal fired plants	892	3316	12.81
PWR plants	1373	3722	4.10
PHWR plants	1532	4563	1.98
LNG plants	516	1379	30.25

TABLE III. CO_2 EMISSION COEFFICIENTS BY FUEL TYPE

	Coal	Oil	LNG
Coefficient (t/toe)	4.32	3.11	2.03
kcal/toe		1.08×10^7	
Caloric value (kcal/kW·h)	2123[a]	2306[b]	1773
t CO_2/MW·h	0.8492	0.6640	0.3333

[a] The values arc based on actual data for the year 1992.

[b] From input data of the ESEP in the Republic of Korea [2].

as close as possible to the official ESEP by using the same data as those used in official planning. In fact, the results of the Reference Case ESEP and the official ESEP are very similar, which confirms the validity of the model specification in this study.

Tables I and II show the input data used in this study. As mentioned earlier, most of the data are identical with those used in official planning. The candidate plants to be introduced during the planning period include PWR and PHWR nuclear power plants, as well as coal fired and liquefied natural gas (LNG) fired power plants. Their unit capacities are 1000 MW, 700 MW, 500 MW and 400 MW, respectively.

Next, the CO_2 constraint is added to the model. The present study assumes two additional ESEPs resulting from the two scenarios mentioned above. Since the amount of CO_2 emissions is quite different for the different power plant options, the amount emitted from each power plant is calculated by using the CO_2 emission coefficient used in this study. Table III shows the CO_2 emission coefficients applied.

4. RESULTS

Table IV summarizes the results for the Reference Case for the weak regulation scenario and for the strong regulation scenario. The results for the Reference Case ESEP are similar to those for the official ESEP. According to the results, the shares of the total installed capacity of nuclear, coal, LNG and other plants are 41%, 28%, 23% and 8%, respectively, by the year 2006.

When the CO_2 emission regulation is taken into consideration, the shares change (see Table IV). In the case of the weak regulation scenario, where the CO_2 emission constraint is added to the model, the shares of nuclear, coal, LNG and other plants are 46%, 26%, 20% and 8%, respectively, by the year 2006. This implies that the shares of both coal and LNG plants decrease and that the share of nuclear plants fills the gap.

In the case of the strong regulation scenario, the shares of nuclear, coal, LNG and other plants change more drastically, to 51%, 18%, 24% and 7%, respectively, by the year 2006. The role of nuclear power is reinforced in this case and the share of LNG increases slightly.

There are many policy alternatives to cope with the externalities produced by CO_2 emissions. Direct control of the quantity of total CO_2 emissions is one of the simplest alternatives. However, direct control does not reflect market forces through which demand and supply adjust themselves. In this regard, a carbon tax may be suggested as a typical policy option to internalize the externalities into the market mechanism.

TABLE IV. ELECTRIC CAPACITY BY SCENARIO (MW(e) and %)

		1994	2000	2006
Reference case	Nuclear	7 616 (22)	13 716 (28)	25 716 (41)
	Coal	11 710 (33)	17 710 (35)	17 710 (28)
	LNG	8 297 (24)	10 697 (21)	14 297 (23)
	Others	7 299 (21)	7 765 (16)	4 729 (8)
	Total	34 922 (100)	49 888 (100)	62 452 (100)
Weak regulation scenario	Nuclear	7 616 (21)	16 416 (33)	28 416 (46)
	Coal	10 210 (29)	15 710 (31)	16 210 (26)
	LNG	10 297 (29)	10 697 (21)	12 697 (20)
	Others	7 299 (21)	7 765 (15)	4 729 (8)
	Total	35 422 (100)	50 588 (100)	62 052 (100)
Strong regulation scenario	Nuclear	7 616 (21)	19 416 (36)	32 816 (51)
	Coal	6 210 (17)	11 710 (21)	11 710 (18)
	LNG	15 497 (42)	15 897 (29)	15 897 (24)
	Others	7 299 (20)	7 765 (14)	4 729 (7)
	Total	36 622 (100)	54 788 (100)	65 152 (100)

TABLE V. MARGINAL COSTS OF CO_2 EMISSION CONTROL FOR THE ELECTRIC SYSTEM (Won/t CO_2)

	2000	2002	2004	2006
Weak regulation scenario	19 717	16 336	0	0
Strong regulation scenario	41 591	23 209	16 520	9668

An optimal carbon tax rate could be based on the marginal cost that would have to be paid by the electric system for a reduction of one unit of CO_2 emission. Because of the intrinsic characteristics of the linear programming model used in this study, the dual value of the CO_2 constraint provides the marginal cost of the electric system.

As shown in Table V, the marginal cost is highest by the year 2000, when the CO_2 emission regulation comes into force, and then it decreases gradually. This implies that the adjustment of the electric system to meet the CO_2 emission constraint is costly at the beginning. In the weak regulation scenario, the marginal cost becomes zero by the year 2004, which implies that the electric system fully adjusts to the regulation. On the other hand, in the strong regulation scenario, the regulation is too strict for the electric system to absorb the whole impact during the planning period. On the basis of these results, the proper carbon tax on the electric system by the year 2000 is suggested to be 19 717 Won/t CO_2 for the weak regulation scenario and 41 591 Won/t CO_2 for the strong regulation scenario. The effect of fully transferring the marginal cost to the fuel cost would be equivalent to an increase in the coal price by 2.3 times the increase in the weak regulation scenario and 3.7 times the increase in the strong regulation scenario by the year 2000. On the other hand, the effect of a fuel cost increase on LNG is not significant for either scenario.

5. CONCLUSIONS

It is clear that the existing ESEP is no longer an optimum plan when the CO_2 emission regulation considered in this study becomes effective. The structure of the electric system should be adjusted in order to meet this regulation; in the meantime, the role of clean energy sources such as nuclear power and LNG should be strengthened. However, this adjustment is costly, whatever the policies used — direct control or carbon tax. It will lead to additional costs for the electric system, which the consumers will have to pay.

The simplest policy option to meet the regulation is direct control of the electric system. However, this policy may give a wrong impression of the role of each energy source. In this regard, the marginal cost of each energy source in the electric system provides valuable information and the cost can be regarded as the proper carbon tax rate for each energy source. If the estimated carbon tax were fully transferred to the fuel cost, then the effect on the price of coal would be significant. This increase in the price of coal is inevitable and will lead to great changes in the relative economic competitiveness of fuels for electricity generation. Therefore, the existing ESEP should be revised and modified when the new regulation of CO_2 emissions is imposed on the electric system.

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INTEGRATED RESOURCE PLAN OF POWER SYSTEM DEVELOPMENT IN POLAND*

L. TWARDY
Polish Power Grid Company

R. KROCHMALSKI
Institute of Power Engineering

Warsaw, Poland

Abstract

INTEGRATED RESOURCE PLAN OF POWER SYSTEM DEVELOPMENT IN POLAND.

The paper presents information on the research activities conducted in Poland under the DECADES project. The beginning of the project is described and some information is given on the programme of the electric industry for expansion of the electricity generation system in Poland and its main issues. The main target of the research under the DECADES project is to analyse the potential role of nuclear power in reducing pollutant emissions from electricity generation. In the first phase, a number of models were used in preliminary calculations, such as MAED for demand forecasts, LDC for the load duration curve, WASP for the electricity system expansion programme and IMPACTS for the emission of gases. On the basis of previous analyses it was assumed that there would be no drastic changes in the power system structure before the year 2000 because of the existing surplus of capacity. The selected planning period was from 2000 to 2030. Preliminary studies of two cases were performed: the base case (construction period for nuclear units of nine years) and the nuclear case (six years). For these two cases, the power system capacity mix, electricity generation and greenhouse gas emissions from electricity generation were calculated and the results are presented in the paper.

1. INTRODUCTION

The paper presents information on the research activities conducted in Poland for the DECADES (databases and methodologies for comparative assessment of different energy sources for electricity generation) project.

* The IAEA Research Contract No. 8366/RB for the Polish Power Grid Company was signed on 31 January 1995.

The agreement between the Polish Power Grid Company and the Institute of Power Engineering on research activities for the DECADES project was established at the end of March 1995. Fortunately, some information and material for the project had been available earlier, so it was possible to begin preparatory work some time ago. This work concerned the scope and target of the project, computer tools (databases, software) and the methodology to be used. Sets of input data were prepared and verified for application in first test calculations that were performed on the basis of the existing software (WASP). The results are discussed below.

Preliminary work was done in connection with the preparation of the material needed for the next activities, including both methodological and information aspects. Concerning methodological aspects, the DECADES working papers on databases, structures and software were utilized. Informational activities were directed at identifying the main data sources, to provide as much information as possible that could be used for the country specific database.

2. ELECTRICITY SECTOR

Poland relies to a very large extent on the use of hard coal and lignite for power generation. About 98% of the country's electricity is produced from solid fuels. There is a strong need for rehabilitation and environmental upgrading of the power plants, which are relatively old (average age 18 years, large emissions of pollutants). Improvement of the environmental performance of power plants has high priority. Western European standards for existing plants are scheduled to come into effect in 1998. There is no immediate need for new capacity in the near future because the electricity demand in Poland is much lower than it was a few years ago. The Polish authorities aim at integrating the Polish electricity system into the western European UCPTE system, for reasons of supply strategy and economy.

Since 1989, the Polish electricity sector has been in a process of restructuring. In the previous centrally planned system, large projects, such as new power plants, were decided on and planned centrally. Reorganization of the electricity sector has resulted in the formation of three groups of companies, dedicated to electricity generation, transmission and distribution. Within each group, the companies are or will be organized as financially independent joint stock companies.

Reorganization of the market for electricity has been proposed. It is envisaged to create a system of contracts between electricity generators and transmission companies in order to guarantee revenues for companies that will have to make significant investments. It is intended that, in the medium to long term, the market will be opened gradually in order to enable competition between electricity generators. At a later stage, electricity generators will be allowed to compete for direct supplies of electricity to distribution companies.

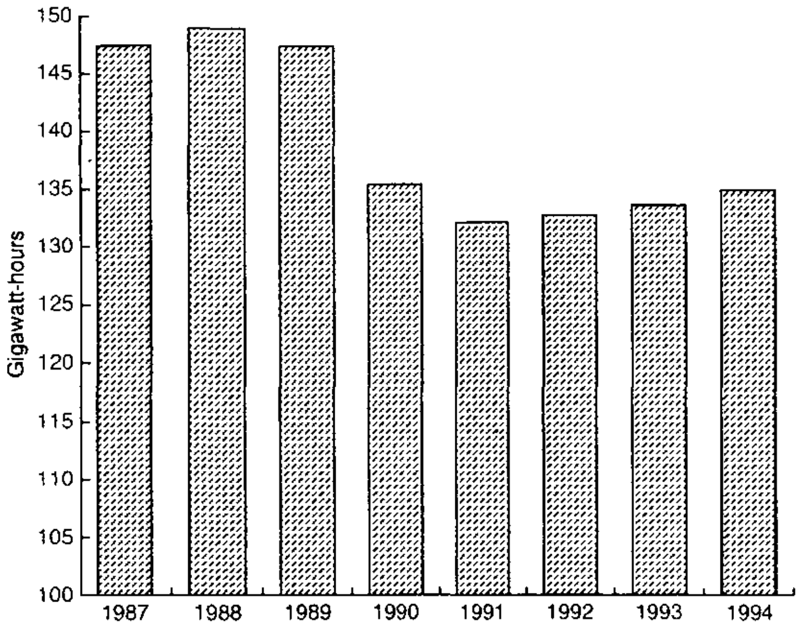

FIG. 1. Electricity generation in Poland.

Economic recession and changes in the structure of the economy have led to a decline in total electricity consumption by almost 18% from 1989 to 1992. In 1993 and 1994 there was some recovery in total electricity consumption (Fig. 1). The fairly strong increases in the electricity demand of the industry and service sectors more than compensated the continued decline in the electricity demand of the residential and agricultural sectors.

The electricity demand will probably continue to increase in the years ahead, in response to economic growth, structural changes and improved efficiency of electricity generation. Taking into account the above mentioned factors, it is evident that the planning process is an extremely difficult task.

3. MAIN DIRECTIONS OF RESEARCH

The programmes of the electric industry for expansion of the electricity generation system in Poland studied so far included mainly the time horizon 2020 or 2025. The results obtained indicate that before the year 2000, no large changes related to the structure of the electricity generation system can be expected. According to the analysis performed, there is no need of investments in new capacities (for the existing power plants, rehabilitation and provision of equipment for environmental protection are needed).

In view of this, it has been assumed for the DECADES studies in Poland that calculations and analyses will be performed for the period 2000–2030. It is clear that for such a long period, investments in new capacity will be required because of the retirement of old power plants and the necessity to cover load increments.

A preliminary assumption is that several alternative variants (cases) of the programme for expansion of the electricity generation system will be calculated and analysed, taking into account the capacity structure, costs, fuel consumption and emission of greenhouse gases. The 'nuclear option' for the development of the electricity generation system will be analysed as one of several possibilities and its impact on costs, fuel consumption and emission of gases will be evaluated. It is possible that the nuclear option will be accepted in Poland if there are insufficient conventional fuels or in the case of international restrictions on pollution.

4. PRELIMINARY CALCULATIONS AND RESULTS

Sets of input data required for the calculation with the WASP model were collected and prepared; these included:

— Forecasts of electricity demand and load,
— Load duration curves for each year of the projected period,
— Projection of fuel prices,
— Investment costs for new technologies (candidates),
— Technical and economic parameters of existing and new generation units,
— Changes in the capacity of existing power plants related to plant retirement and rehabilitation,

and some general assumptions, such as the value of the discount rate (12% for the preliminary calculations) and the loss of load probability (LOLP, 0.274%).

4.1. Base case

As a result of the calculations with the WASP model, the base case of the electricity generation system in Poland for the period 2000–2030 was obtained. To achieve the required available capacity of the electricity generation system, new power plants of about 46 GW installed capacity are required, consisting of 18.7 GW hard coal fired plants, 4.75 GW lignite fired plants, 8.7 GW natural gas fired plants with peak load turbines, and 13.8 GW natural gas fired, combined cycle plants. No nuclear power plants are included in the base case.

Figures 2–4 show the power system capacity mix, the electricity generation and the greenhouse gas emissions from electricity generation. These emissions were roughly estimated on the basis of average emission indicators from different types of generation units and fuels. Restrictions on NO_x emissions were assumed because

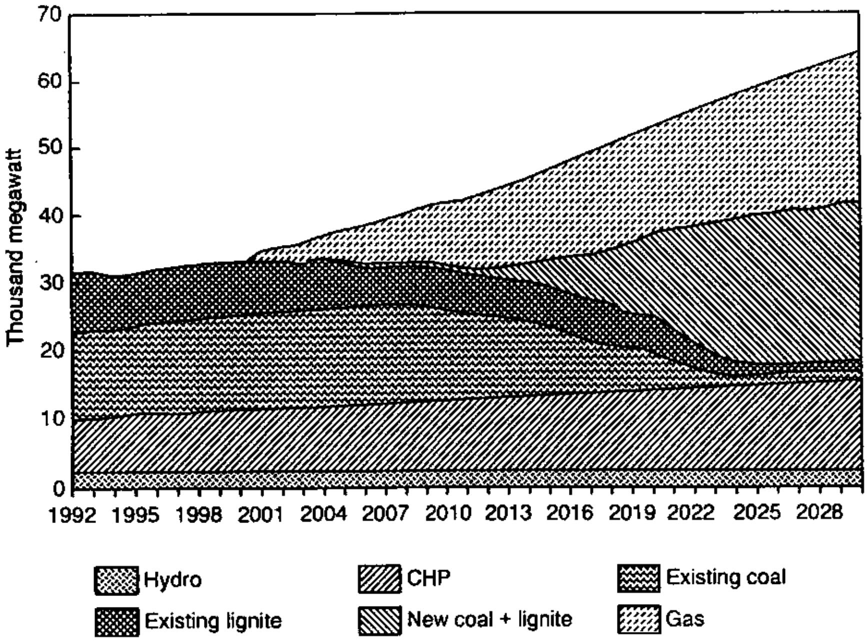

FIG. 2. Power system capacity mix — base case.

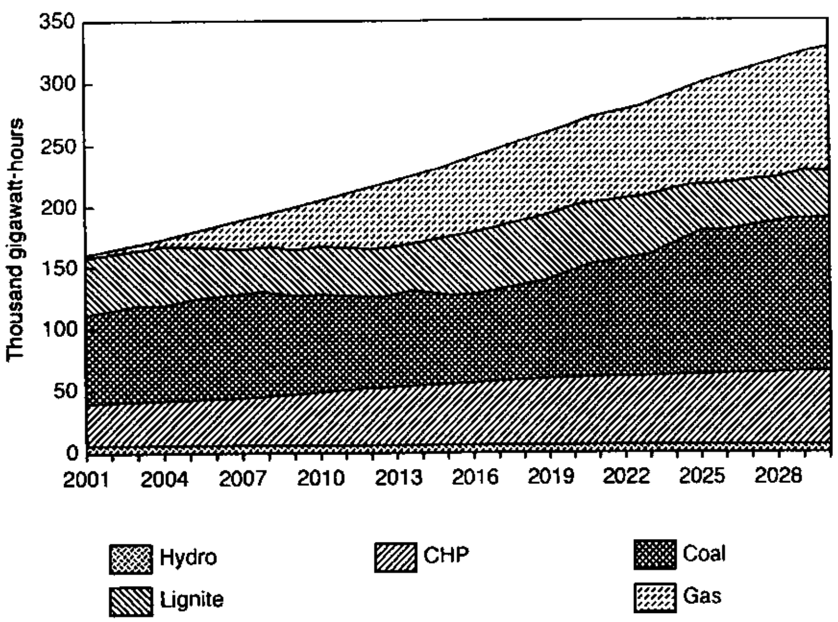

FIG. 3. Electricity generation — base case.

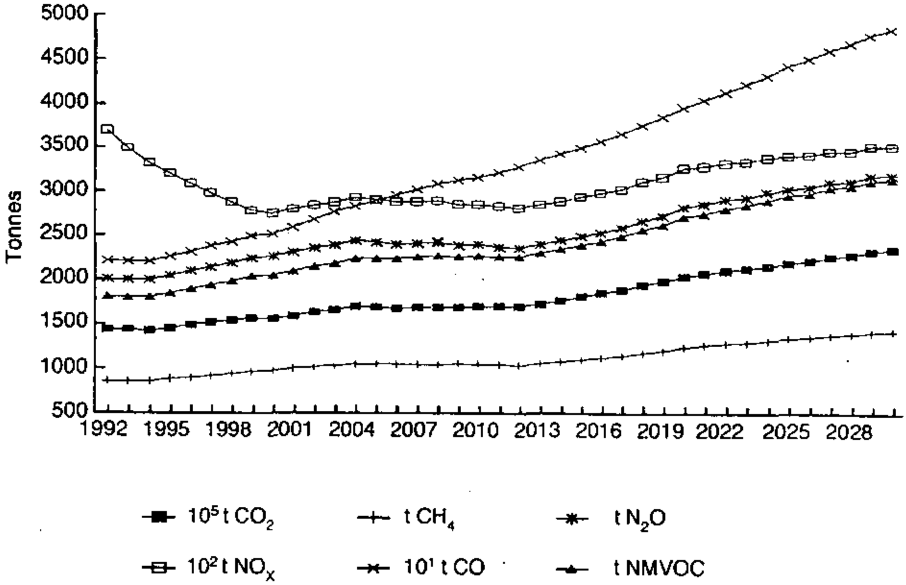

FIG. 4. Greenhouse gas emissions from electricity generation — base case.

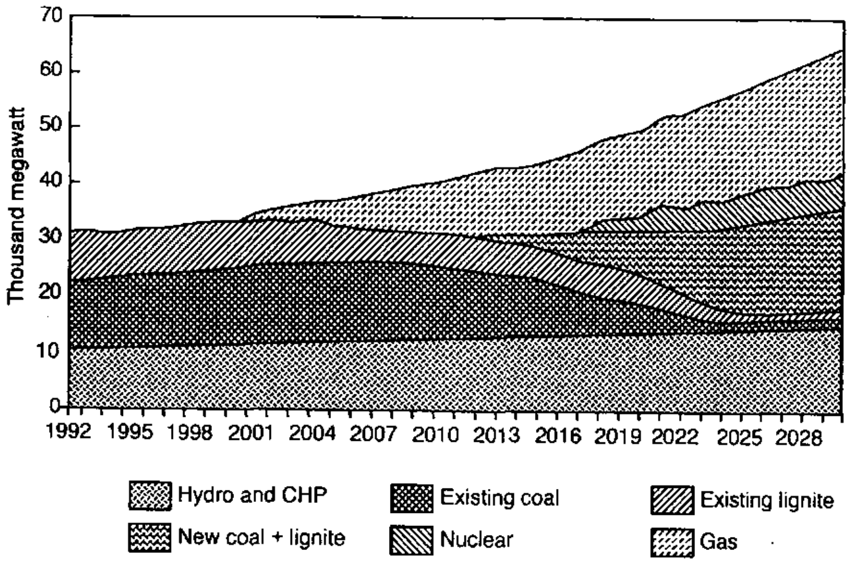

FIG. 5. Power system capacity mix — nuclear case.

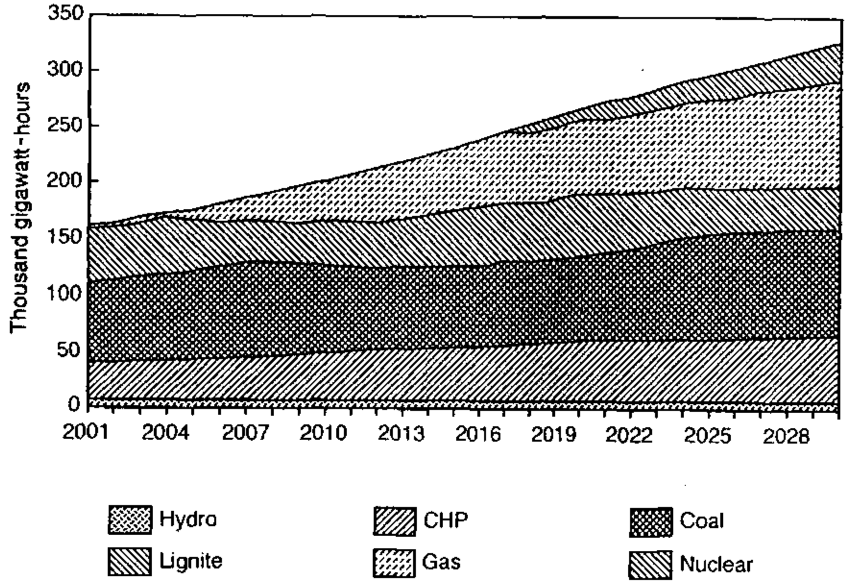

FIG. 6. Electricity generation — nuclear case.

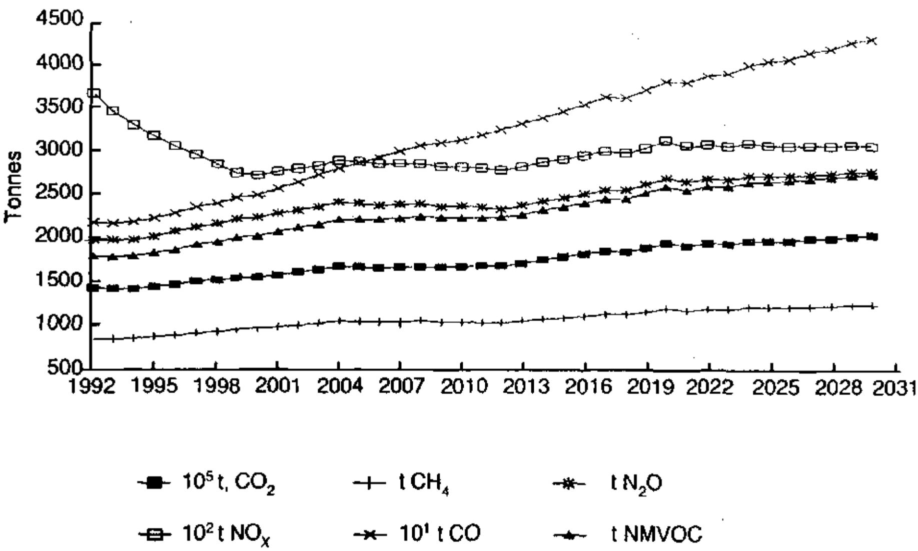

FIG. 7. Greenhouse gas emissions from electricity generation — nuclear case.

of new regulations for 1998. The increase in greenhouse gas emissions is due to the increasing consumption of conventional fuels.

4.2. Nuclear case — alternative variant

Preliminary calculations with the WASP model, using the same input data as for the base case, were made for the 'nuclear option' of the electricity generation system expansion programme. The construction period of new nuclear units was the only difference introduced. It was assumed that advanced type nuclear units to be constructed after the year 2010 can be built in a time period that is three years shorter than the construction time assumed for the base case, i.e. the construction period for these units would be six years. The optimal solution for the nuclear case was to put nuclear units into operation from the year 2018.

In order to obtain the required capacity at the end of the project period, new investments in plants of about 47 GW will have to be made, including 14 GW hard coal fired units, 5.4 GW nuclear units, 4.75 GW lignite fired units, 8.7 GW natural gas fired units with peak load turbines, and about 14 GW natural gas fired, combined cycle units.

Figures 5–7 show the power system capacity mix, the electricity generation and the greenhouse gas emissions from electricity generation for the nuclear case. It was found that a substantial reduction of greenhouse gas emissions can be achieved with the nuclear option.

Further studies have to be performed to analyse the implementation of nuclear units under different economic and environmental conditions (lower discount rate, higher conventional fuel prices or constraints on their availability, the same limits of greenhouse gas emissions as for the base case, etc.).

5. NEXT RESEARCH ACTIVITIES

Further evaluation and analyses of all data, calculations and results presented here are required. Any new information, particularly from the DECADES databases, will be considered. Future activities will include:

— Preparation of a country specific database,
— Implementation of available new software,
— Comparative assessment of alternative variants of different energy sources for electricity generation under various conditions and constraints,
— Analysis of greenhouse gas emissions from the plants considered in this study.

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DEVELOPMENT OF THE REGIONAL CAPACITY EXPANSION PLAN IN RUSSIA
Application of the WASP Model

Yu.F. CHERNILIN, S.L. KONONOV, E.F. ZAKHAROVA
Russian Research Centre, Kurchatov Institute,
Moscow

V.S. KAGRAMANYAN, A.V. MALENKOV
State Scientific Centre,
Institute of Physics and Power Engineering,
Obninsk

Russian Federation

Abstract

DEVELOPMENT OF THE REGIONAL CAPACITY EXPANSION PLAN IN RUSSIA: APPLICATION OF THE WASP MODEL.

The Wien Automatic System Planning Package (WASP) has been used for the development of an optimal capacity expansion plan for the power sector in Russia. The object of the WASP study is the Central Power Pool, which is the largest power pool in Russia and has an essential share of nuclear power in electricity generation. The objective of the study is to assess the long term competitiveness of nuclear power in the region. Major features of the model of the power system have been developed with WASP; the following items have been considered: four types of electricity generators: condensing fossil fuel plants, cogeneration fossil fuel plants, nuclear power plants and hydropower plants; nine fuel categories: the gas/fuel oil fuel, several types of coal and several nuclear fuels; and a model of the escalation of capital, operation and maintenance and fuel costs as a result of the economic transition. A regional optimal capacity expansion plan has been developed. The following conclusions can be drawn: (1) Until the year 2004, there will be no need for new electricity generation capacities because of the drop in demand in the 1990s, a certain lifetime margin of existing capacities, predetermined inputs of cogenerators and planned refurbishment/repowering measures. (2) The structure of the optimal capacity mix confirms that nuclear power can retain its role as one of the major electricity generation sources in the region. The most important factor with a positive effect upon the competitiveness of nuclear power plants is the projected escalation of the price of fossil fuels. (3) The application of WASP has proved that the model can serve as a valuable planning tool for power pools in Russia.

1. INTRODUCTION AND BACKGROUND

In the current period of economic transition in Russia, elaboration of a sound capacity expansion strategy for the power sector is an important requirement because of the long term development in this sector and the large financial investments required. Such a strategy is especially important for the nuclear component of the power sector, which is one of the major electricity sources in Russia but which is undergoing large structural changes because of the general economic crisis and the consequences of the Chernobyl accident.

In the process of developing a capacity expansion strategy, it is highly desirable to utilize a sound methodology that allows the related technical, economic and environmental issues to be properly incorporated into the capacity expansion plan and thus provides reliable information backup for decision makers. In this respect, the use of energy planning tools supported and distributed by the IAEA, which are widely used for energy planning purposes in many countries, may be a valuable input into the process of strategy development and, as a complement to other national studies, provide important information for making decisions on the further development of nuclear power in Russia.

This paper highlights some of the activities undertaken in the course of a two-year research project aimed at the assessment of the long term role of nuclear power in Russia with the use of the IAEA planning models. This was part of the country

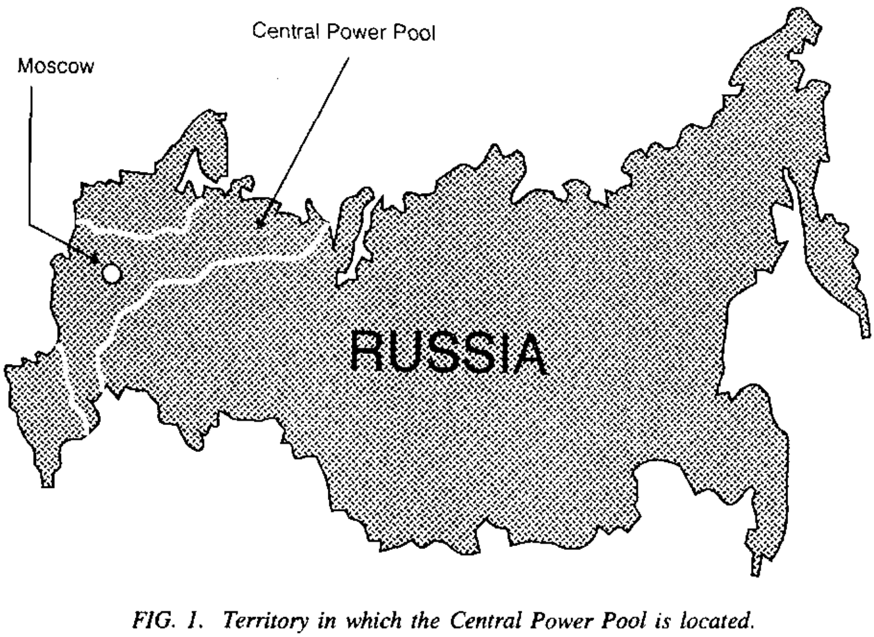

FIG. 1. Territory in which the Central Power Pool is located.

studies performed in the framework of the inter-agency joint project on databases and methodologies for comparative assessment of different energy sources for electricity generation (DECADES) initiated by the IAEA.

Several IAEA planning tools were applied in the course of the project. They included some modules of the ENPEP [1] package, the Wien Automatic System Planning Package (WASP) [2] being one of them, and the DECADES [3] database system. This paper concentrates on the application of the WASP model, which was the most important part of the project. The latest version of WASP (WASP-III Plus [4]) was used.

A power pool serving a large territory in the centre of the European part of Russia was selected as the object of the WASP study. This power pool, called the Central Power Pool (CPP), is the largest component of the integrated power system of Russia, which includes seven such pools. The installed capacity of the CPP is ~50 GW or about one fourth of the total electricity generation capacity in Russia. Most of the electric load is concentrated in the region itself; the share of power exports is only about 5% of the load. The objective of the WASP study was to perform an analysis of the whole regional power system for assessing the long term competitiveness of nuclear power in the region.

The region considered (see Fig. 1) has a territory of about two million km^2 (about 12% of Russia); the population (about 50 million) represents one third of the total population of the country. This is an industrial region, the share of the industry of the total gross product of the region being about 60%.

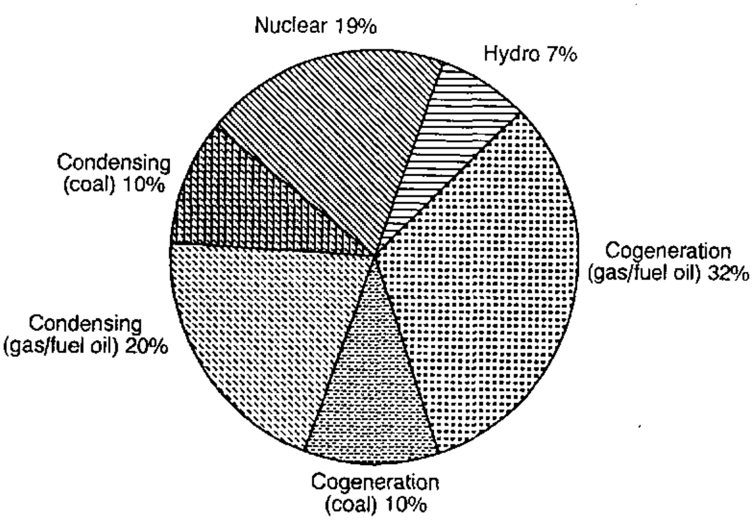

FIG. 2. Breakdown of capacities by type and fuel (1993 data); total capacity = 56.2 GW.

2. APPROACH TO MODELLING OF THE POWER SYSTEM

In 1993, the installed capacity of the CPP was about 56 GW [5]. There are more than 80 power plants in the system. They include condensing and cogeneration plants using fossil fuels, nuclear power plants and hydropower plants (see Fig. 2), including one pump storage plant near the town of Zagorsk in the Moscow province. The dominating energy source for electricity generation is natural gas, but nuclear power is an essential part of the system. In 1993, nuclear power plants produced 23.9% of the total electricity generated in the pool [6]. To successfully model this system with WASP, the following issues have been considered in the study.

2.1. Representation of unit diversity

There are plants of various types in the system: fossil fired units for generation and cogeneration, nuclear units and hydropower plants. Within each of these plant categories, the units differ widely in size (capacity), heat rate and other technical and economic parameters. To describe this system in WASP format, groups of identical units are selected from all actual plants and combined into several representative groups that can also be called 'fictitious plants'. Each fictitious plant includes units that are identical or have similar parameters (unit type, capacity, technical characteristics), and units that use the same fuel. As a result, all power generating units are divided into four groups, as shown in Tables I-IV: condensing fossil fuel plants (Table I), cogeneration fossil fuel plants (Table II), nuclear power plants (Table III) and hydropower plants (Table IV).

To model the differences in the technical conditions of the units, some plausible schedule of planned retirement is developed on the basis of the current equipment status and retirement plans [7, 8]. Furthermore, some fixed additions to the power system are included to represent the processes of refurbishment/repowering and the introduction of units that are almost completed and thus are not subject to system optimization [7, 8]. The cogeneration part of the power system is also modelled as a fixed part and thus is excluded from optimization (see below).

2.2. Representation of fuel diversity

For modelling purposes, the fuels consumed in the CPP are broken down into several representative categories (see Tables V–VII). The principle of disaggregation is to explicitly represent the types of coal used most often and to combine the types that are used less frequently into fictitious categories. Also, natural gas and fuel oil are treated as one fuel, denominated 'gas/fuel oil'. (Currently, the share of fuel oil in this combined fuel is of the order of 10% and is expected to further decline in

Text continued on page 750.

TABLE I. REPRESENTATION OF CONDENSING FOSSIL FUEL PLANTS [5, 10]

Name in WASP	Type of unit and fuel used	Number of units	Available capacity		Representative characteristics (1990–1991)	
			MW(e)	(% of total)	Heat rate (gce/kW·h)[a]	Capacity factor (%)
KG0F	K-1200 (gas/fuel oil)	1	1 200	7	314.1	75.5
KG1F	K-800 (gas/fuel oil)	2	1 600	9	323.5	73.5
KG3F	K-300 (gas/fuel oil)	19	5 700	33	325.9	68.9
MGDF	MGD-310 (gas)	1	310	2	323.5	68.9
KG4F	K ~ 200 (gas/fuel oil)	9	1 880	11	346.4	64.8
GTUF	GTU ~ 100 (gas turbine)	7	778	5	572.6	6.7
Total	Total for gas/fuel oil plants	39	11 468	67	—	—
KC3F	K-300 (Kuznetsky coal)	6	1 800	10	369.3	62.5
KM3F	K-300 (Moscow coal)	4	1 120	7	366.2	57.9
KM4F	K-200 (Moscow coal)	3	600	3	411.2	53.5
KI4F	K ~ 200 (Intinsky coal)	6	1 230	7	377.6	63.8
KC5F	K ~ 150 (Kuznetsky coal)	4	525	3	404.8	75.2
KL6F	Other (local coals)	—	418	2	406.7	57.6
Total	Total for solid fuel plants	—	5 693	33	—	—
Total	Total for all condensing plants	—	17 161	100	—	—

[a] gce = grams of coal equivalent.

TABLE II. REPRESENTATION OF COGENERATION FOSSIL FUEL PLANTS [5, 10]

Name in WASP	Type of unit and fuel used	Number of units	Available capacity		Representative characteristics (assessment)	
			MW(e)	(% of total)	Heat rate (gce/kW·h)	Capacity factor (%)
TG_	Gas-fired cogeneration plants	—	18 302	76	240 (el.) 470 (el.+heat)	70
TN̄_	Cogeneration plants on Kuznetsky coal	—	2 300	9	255 (el.) 505 (el.+heat)	65
TL_	Cogeneration plants on other coals	—	3 600	15	265 (el.) 515 (el.+heat)	65
Total	All plants	—	24 202	100	—	—

TABLE III. REPRESENTATION OF NUCLEAR POWER PLANTS [5, 10, 11]

Name in WASP	Type of unit	Number of units	Available capacity		Representative characteristics (1991–1993)	
			MW(e)	(% of total)	Heat rate (gce/kW·h)	Capacity factor (%)
RBMK	RBMK-1000	7	7 000	65	425.2	71.3
V320	WWER-1000	3	3 000	27	382.8	67.2
V230	WWER-440	2	834	8	419.4	62.6
Total	All NPPs	12	10 834	100	—	—

TABLE IV. REPRESENTATION OF HYDROPOWER PLANTS [5, 10]

Name in WASP	Unit location (plant denomination and location in Russia)	River	Installed capacity (MW(e))	Available capacity		Representative characteristics (1991)	
				(MW(e))	(% of total)	Electricity served (TW·h/year)	Capacity factor (%)
NIZH	Nizhegorodskaya HPP (Nizhny Novgorod)	Volga	520	485	11	2.123	46.6
RYBU	Rybinskaya HPP (Yaroslavl' province) + Uglichskaya HPP (Yaroslavl' province)	Volga	440	370	9	1.823	47.3
VOLZ	Volzhskaya NPP-1(22) (Volgograd)	Volga	2541	2426	57	12.950	58.2
ZAGO	Zagorskaya PSP (Moscow province)	—	800	774	18	0.672	9.6
AGGR	Other (small) plants	—	187	187	4.2	0.158	9.6
Total		—	4488	4242	100	—	—

TABLE V. CHARACTERISTICS OF THE FOSSIL FUELS USED [9]

WASP No.	Fuel type (denomination in WASP)	Contents			Low heating value		
		Ash (wt%)	C (wt%)	S (wt%)	MJ/kg	kcal/kg	CE[a]
0	Gas/fuel oil (GM):						
	• natural gas[b]	—	75.0	—	34.4	8224	1.17
	• fuel oil[c]	0.13	84.7	3.0	39.9	9536	1.36
2	Kuznetsky coal (KUZN)[d]	14.7	68.4	0.3	25.8	6160	0.88
3	Moscow coal (MOSC)	28.0	39.6	3.0	10.4	2490	0.36
4	Intinsk coal (INTA)	25.7	53.8	2.7	18.3	4370	0.62
5	Kansk-Achinsk coal (K-AC)[e]	6.8	50.3	0.2	15.7	3740	0.53

[a] CE = coal equivalent, defined as the heat content of the fuel divided by 7000 kcal/kg.
[b] Gas from the Tyumen region is taken as representative.
[c] Fuel oil M-100 from the Moscow refinery is taken as representative.
[d] Coal of the CC type is taken as representative.
[e] Borodinsky coal is taken as representative.

TABLE VI. CHARACTERISTICS OF THE NUCLEAR FUELS USED [8]

WASP No.	NPP type (fuel denomination in WASP)	Fuel type	Enrichment (wt% of ^{235}U)	Average burnup (GW·d/t U)
8	RBMK-1000 (NUCR)	UO_2	2.4	21
7	WWER-440 and NP-500 (NUCV)	UO_2	3.5	29 (WWER-440) 40 (NP-500)
9	WWER-1000 and NP-1000 (NUCN)	UO_2	4.4	40 (WWER-1000) 43 (NP-1000)

TABLE VII. REFERENCE COST PARAMETERS OF FUELS (END OF 1994) [5]

WASP No.	Fuel type (denomination in WASP)	Cost in physical units	Cost in energy units (US $/tce)	Cost in WASP units (¢/million kcal)
0	Gas/fuel oil (GM)	US $35.1/1000 m^3	30	429
2	Kuznetsky coal (KUZN)	US $20.2/t	23	329
3	Moscow coal (MOSC)	US $5.4/t	15	214
4	Intinsk coal (INTA)	US $14.3/t	23	329
5	Kansk-Achinsk coal (K-AC)	US $11.1/t	21	300
6	Local coals (CLOC)	—	15	329
8	RBMK-1000 (NUCR)	3.8 mills/kW·h	8.94	128
7	WWER-440 and NP-500 (NUCV)	3.7 mills/kW·h (WWER-440)	8.82 (WWER-440)	126 (WWER-440)
		2.4 mills/kW·h (NP-500)	6.50 (NP-500)	93 (NP-500)
9	WWER-1000 and NP-1000 (NUCN)	3.2 mills/kW·h (WWER-1000)	8.36 (WWER-1000)	119 (WWER-1000)
		2.8 mills/kW·h (NP-1000)	7.86 (NP-1000)	112 (NP-1000)

the future.) For nuclear fuels, the most typical types are represented specifically, the reason being the importance of nuclear power in the region and the emphasis on nuclear power in the study.

2.3. Modelling a large share of cogeneration

Cogeneration plants provide about 40% of the total electricity generation in the CPP. However, WASP does not have the means to represent the process of cogeneration specifically. Instead, there are some indirect ways of simulating cogeneration. The following approach is applied in this study:

(a) Cogeneration units, like common condensing units, are grouped according to unit capacity and fuel type, as described above.
(b) Each cogeneration unit is described in the WASP data format in exactly the same way as condensing units are. To reflect the actual fuel consumption, all capital, fuel and O&M costs are allocated to the generated electricity.
(c) The cogeneration system is modelled as a subsystem with some predetermined plan of development. This plan is taken from the current Russian plans [5, 7].

On the basis of this approach, the share of cogeneration in the system and its development are simulated and, accordingly, the share of the electricity demand to be covered by cogeneration units is determined and deducted from the total demand. This allows the WASP optimization process to be carried out only for condensing units, in accordance with the conventions of the model. However, the exclusion of cogeneration from optimization is a significant drawback, which calls for detailed separate analysis.

2.4. Definition of expansion candidates

The electricity generation technologies considered as expansion candidates in the study include gas fired units (both traditional and combined cycle units); coal fired units using various types of coal (Kuznetsky coal and Kansk–Achinsk coal are the predominant ones) and various combustion technologies (pulverized coal, fluidized bed combustion); and nuclear units of various design (see Table VIII). Among the latter, two evolutionary projects are considered as the most promising for the future: the NP-500 and the NP-1000 nuclear power plants [11, 12].

2.5. Definition of basic economic parameters

The basic economic parameters for the expansion candidates are given in Table IX. Two values for each economic parameter are given: one for the year 1994 and the other one for the year 2010. It is assumed that capital and operation costs will escalate as a result of the market transition process, reaching by the year 2010

TABLE VIII. TECHNICAL PARAMETERS FOR THE EXPANSION CANDIDATES [5, 10, 11]

Name in WASP	Type of unit and fuel used	Fuel number in WASP	Operating capacity (MW(e))		Heat rates (gross), gce/kW·h (kcal/kW·h)		Reliability parameters	
			Minimum	Maximum	At minimum power	At maximum power	Forced outage rate (%)	Planned outages (days/year)
VGAS	K-300 [10] (gas/fuel oil)	0	200	300	329 (2303)	315 (2205)	5.6	40
VKAN	K-500/pulverized [8] (Kansk-Achinsk coal)	5	430	500	329 (2303)	325 (2275)	6.6	46
VKUZ	K-300/pulverized [8] (Kuznetsky coal)	2	260	300	329 (2303)	325 (2275)	6.6	46
VCLK	K-320/AFBC [11] (Kuznetsky coal)	2	260	320	329 (2303)	325 (2275)	6.6	46
VN05	NP-500 [8, 12] (nuclear fuel)	7	615	635	350 (2450)	350 (2450)	3.0	60
VN10	NP-1000 [8, 11, 12] (nuclear fuel)	9	1070	1100	335 (2345)	335 (2345)	3.0	60
VCCG	CC-360 [5, 11] (gas/fuel oil)	0	250	360	266 (1862)	253 (1771)	5.6	40
VGTU	GTU-150 [7, Vol. 4] (gas turbine)	0	150	150	411 (3080)	411 (3080)	2.2	21

TABLE IX. ECONOMIC PARAMETERS FOR THE EXPANSION CANDIDATES [5, 10, 11][a]

Name in WASP	Type of unit and fuel used	Base construction cost (BCC) (US $/kW(e) (gross))	Interest during construction[b] (IDC) (% of BCC)	Total construction cost (BCC+IDC) (US $/kW(e) (gross))	Operation and maintenance costs	
					Fixed (US $/kW(e)·month) (US $/kW(e)·year)	Variable (US $/MW·h)
VGAS	K-300	550	29.9	715	1.70 (20.4)	—
	(gas/fuel oil)	820	29.9	1065	2.53 (30.3)	
VKAN	K-500/pulverized	752	29.9	977	2.57 (30.8)	—
	(Kansk–Achinsk coal)	1286	29.9	1671	4.39 (52.7)	
VKUZ	K-300/pulverized	816	29.9	1061	2.79 (33.5)	—
	(Kuznetsky coal)	1398	29.9	1815	4.78 (57.3)	
VCLK	K-320/AFBC	964	29.9	1253	2.98 (35.7)	3.86
	(Kuznetsky coal)	1432	29.9	1861	4.42 (53.0)	5.73
VN05	NP-500	793	38.5	1098	5.93 (71.1)	—
	(nuclear fuel)	1565	38.5	2167	8.73 (104.8)	
VN10	NP-1000	714	38.5	988	4.23 (50.8)	—
	(nuclear fuel)	1299	38.5	1799	6.47 (77.6)	
VCCG	CC-360	599	22.4	733	2.40 (28.8)	—
	(gas/fuel oil)	903	22.4	1105	3.61 (43.3)	
VGTU	GTU-150	530	12.2	595	1.55 (18.6)	—
	(gas turbine)	790	12.2	886	2.30 (27.7)	

[a] First line: 1994, second line: 2010.

[b] Calculated at a discount rate of 12%.

TABLE X. REFERENCE COST PARAMETERS OF FUELS (forecast for the year 2010) [5, 8]

WASP No.	Fuel type (denomination in WASP)	Cost in physical units	Cost in energy units (US $/tce)	Cost in WASP units (¢/million kcal)
0	Gas/fuel oil (GM)	US $111/1000 m^3	95	1357
2	Kuznetsky coal (KUZN)	US $60/t	68	971
7	Nuclear fuel for WWER-440 and NP-500 (NUCV)	7.3 mills/kW·h (WWER-440)	17.4 (WWER-440)	249 (WWER-440)
		4.8 mills/kW·h (NP-500)	13.0 (NP-500)	186 (NP-500)
9	Nuclear fuel for WWER-1000 and NP-1000 (NUCN)	6.3 mills/kW·h (WWER-1000)	16.5 (WWER-1000)	236 (WWER-1000)
		5.5 mills/kW·h (NP-1000)	15.4 (NP-1000)	220 (NP-1000)

a level close to that in developed countries. The specific assumptions regarding the escalation rates for capital costs are taken from the studies performed in support of the Joint US–Russian Energy Alternatives Study [5], except for the projection of the costs of nuclear units by the year 2010. The latter are assessed in accordance with the data in Ref. [13]. (As projected in Ref. [5], the specific capital costs for Russian nuclear units are assumed to be 10% lower than those of US nuclear units.) As can be assessed using the data in Table IX, the annual escalation rates for capital and operation costs are: ~2.5% for gas fired units and gas turbines, ~3.4% for coal fired units, and for nuclear units ~3.8% for NP-500 and ~3.7% for NP-1000.

2.6. Definition of fuel cost escalation factors

In addition to the escalation of capital and operation costs, the escalation of fuel costs to the price level on the world market is also part of the consequences of the transition to market economy. The scenario of fuel price escalation is taken from Ref. [5]. The resulting forecast of fuel costs for the year 2010 (end of the escalation period) is given in Table X.

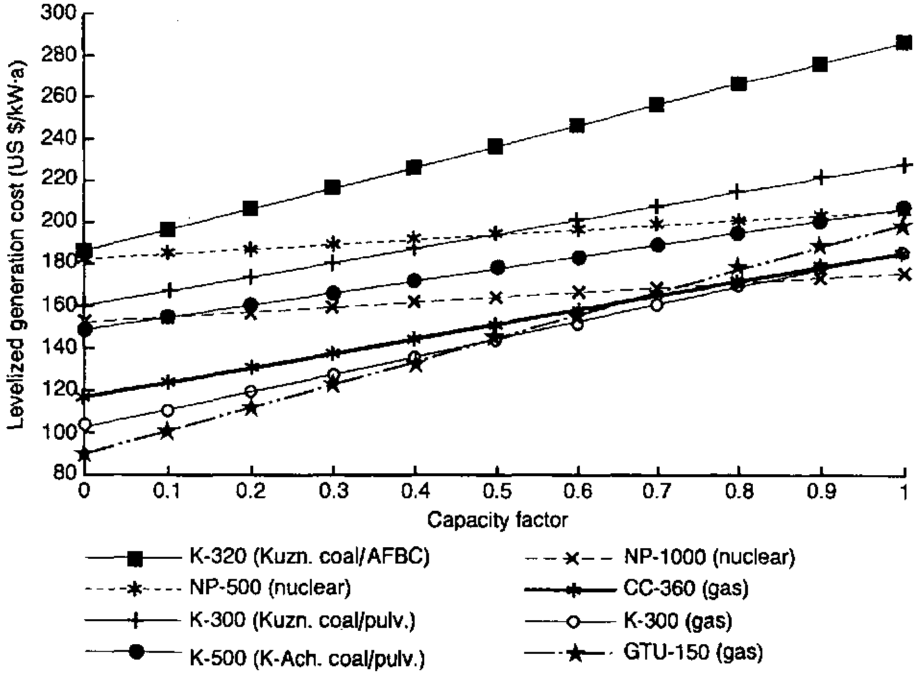

FIG. 3. Screening curves of candidates for the year 1994.

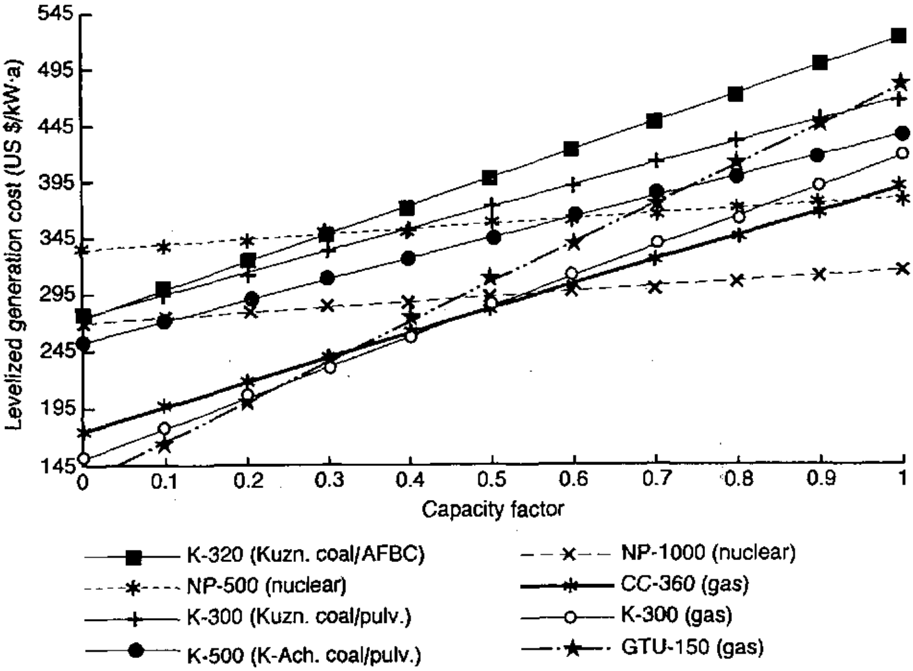

FIG. 4. Screening curves of candidates for the year 2010.

Note the differences in the fuel cost escalation rates: gas/fuel oil ~7.5%/a, coal ~7.0%/a, and nuclear fuel ~4.3%/a. The lower rates for nuclear fuel should be emphasized. This is one of the potential sources of the economic competitiveness of nuclear power in the future.

2.7. Economic screening of the candidates

Before starting the optimization procedure, screening curves were analysed to compare the different candidates, in order to identify the better technologies and thus reduce the dimension of the optimization problem. In Figs 3 and 4 it can be seen that the economic competitiveness of the candidates changes with time as a result of the assumed escalation of capital, operation and fuel costs. The most important change is that, because of the accelerated escalation of fuel costs, the most efficient technologies regarding fuel consumption are gaining in economic terms. Such technologies include the combined cycle units and the nuclear units of NP-1000 design. Thus, for the system relying heavily on natural gas under the conditions of the year 1994 there is a trend to a combined gas–nuclear composition under the conditions of the year 2010. Coal fired plants do not appear attractive because of both high capital costs and relatively high fuel costs.

3. RESULTS OF THE WASP STUDY

3.1. Optimal capacity expansion plan: Structure and implications

The structure of the optimal capacity expansion plan developed with WASP-III Plus is shown in Figs 5 and 6. Figure 5 illustrates the structure of the whole electricity generation system, including previously existing capacities (in both cogeneration and condensing units), electricity generators with predetermined inputs, and the capacities of new condensing units determined as a result of the WASP optimization procedure. Figure 6 includes only newly constructed units, i.e. the condensing electricity generators selected by WASP for construction. Thus, Fig. 6 shows the structure of the optimal solution. The characteristic features of the optimal capacity expansion plan are as follows:

- Before the year 2004 there is no need for new electricity generation capacities because of the drop in demand in the 1990s, a certain lifetime margin of existing capacities, predetermined inputs of cogenerators and planned refurbishment/repowering measures.
- For the system as a whole (Fig. 5), there are no drastic changes over the period considered. The shares of gas fired and hydropower plants increase slightly, while the shares of nuclear and coal units decrease slightly. At the same time, the detailed structure of the variable part of the system, i.e. the optimized one, does show some essential changes.
- The optimal solution includes four types of electricity generation units: combined cycle units, conventional gas fired units, nuclear units and gas turbines.
- As shown in the screening curve analysis, at the beginning of the planning period (1994) gas fired technologies were the best ones economically because of the rather low gas prices at that time. However, as gas and coal become more and more expensive, reflecting accelerated escalation of fossil fuel prices, nuclear power becomes competitive and nuclear units start to enter the optimal solution. As a result, it is the nuclear unit that enters the system first when new capacities are required (2004). At the end of the period considered (2015) there are two nuclear units in the system. The remaining part of the new capacities includes mostly gas fired units, with combined cycle units being predominant. This is a consequence of the ability of gas fired units to serve half-peak and peak loads, while nuclear units are competitive only when working at base load. The latter effect is accentuated by the modelled changes in the load curves, i.e. by the unevenness of load growth with time.
- In the optimal solution there are no inputs of new coal fired units, the reason being the too high capital costs (see the screening curves for coal in Figs 3 and 4).

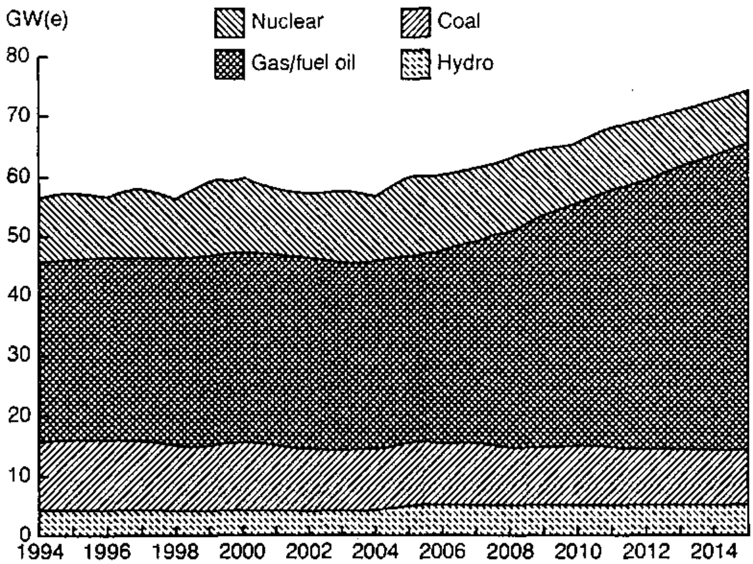

FIG. 5. Structure of the optimal capacity expansion plan.

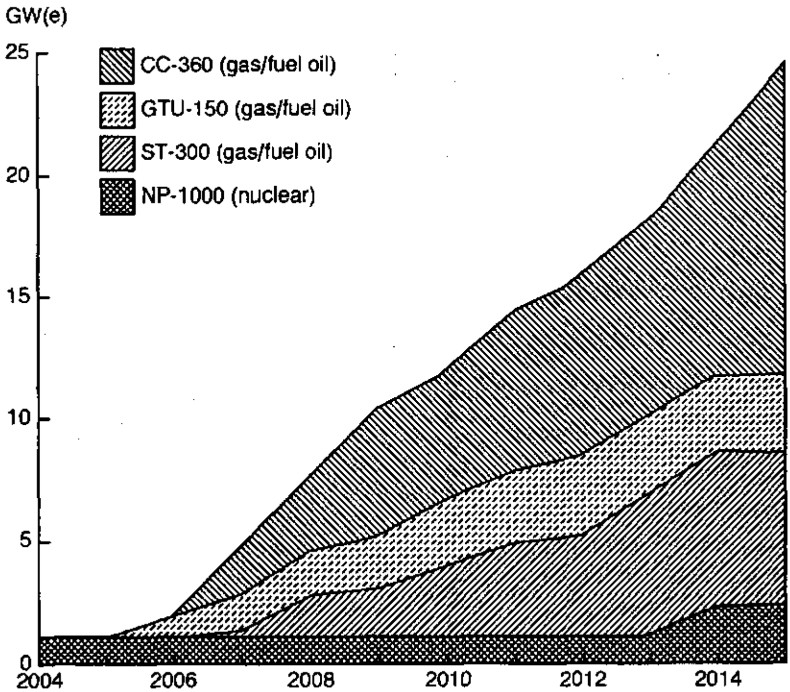

FIG. 6. Composition of the variable system (input of new capacities).

In general, the composition of the optimal solution confirms the conclusion that can also be drawn from the screening curve analysis: while at low fossil fuel prices the competitiveness of nuclear power might be questioned, the accelerated escalation of these prices to world market levels increases the economic advantages of nuclear power and nuclear units become part of the optimal capacity expansion plan.

3.2. Sensitivity analysis

Because of the general economic and social instability in Russia, a sensitivity analysis is required in order to assess the impact of various uncertainties on the optimal composition of the electricity generation system. In the course of this analysis, all sensitivities are conditionally broken down into four groups: (1) sensitivities to demand uncertainties (e.g. to higher/lower demand growth rates); (2) sensitivities to economic uncertainties (e.g. to the value of the discount rate); (3) sensitivities to social uncertainties (e.g. to the acceptance of nuclear power); and (4) sensitivities to system uncertainties (e.g. to the value of the reserve margin). Some representative results of the sensitivity analysis are illustrated in Figs 7 and 8. In respect of the long term role of nuclear power, these results are summarized as follows:

— In the low demand scenario, nuclear units are put on line much later than in the reference case — in the year 2009 as compared with the year 2004 in the reference case. However, the share of nuclear units of the units commencing operation after the year 2009 is much higher than in the reference case. The reason for this is obvious: in the low demand case the electricity deficit appears later, but it is exactly in this period (2005–2010) that the escalation of fossil fuel prices makes nuclear power preferable. Thus, in a way, nuclear power appears more attractive under the low demand scenario than under the average demand scenario.

— In the high demand scenario, the share of nuclear units in the variable system is lower than that in the low demand scenario. However, in absolute terms, the share of nuclear power is higher: by the year 2015 there should be five new 1000 MW(e) nuclear units as compared with only two such units in the reference case. Thus, the high demand scenario also includes nuclear power as an essential part of the optimal solution.

Thus, the sensitivity analysis has confirmed that nuclear power has some potential for competitiveness in the system, notwithstanding variations in the projected load factor and some other factors. Moreover, some variations result in a significantly higher share of nuclear power in the system than that in the reference case. Of course, these results are only applicable to the region considered and some other sensitivities may show decreased shares of nuclear power (e.g. a 10% increase in the capital cost for the nuclear candidate results in the absence of nuclear units in

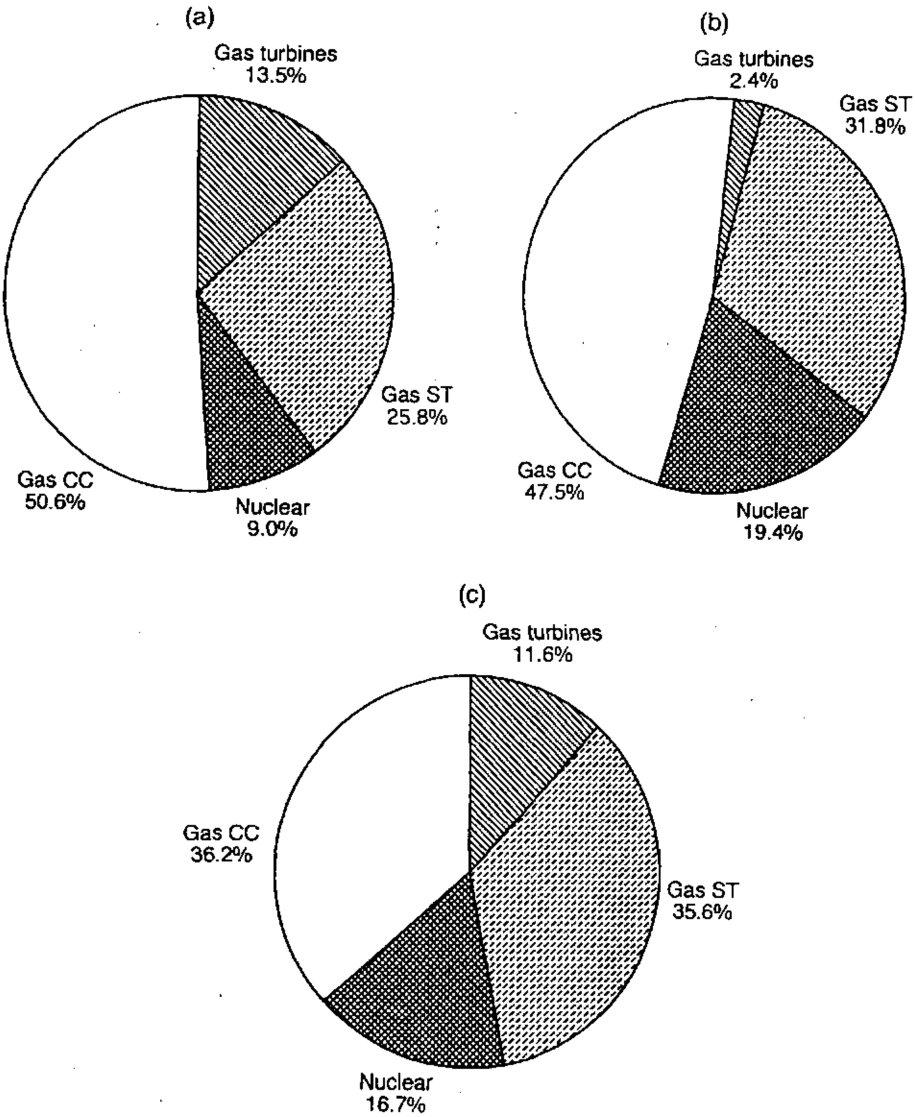

FIG. 7. Structure of new capacities for the reference case and the sensitivity cases (in per cent of the total installed capacity of new units entering the system by the year 2015). (a) Reference case, (b) low demand case, (c) high demand case.

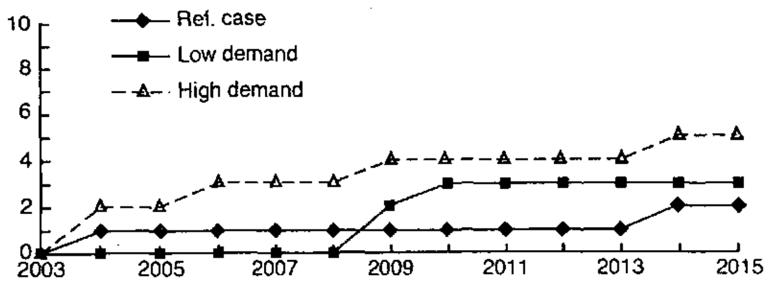

FIG. 8. Number of new nuclear units for the reference case and the sensitivity cases.

the optimal solution). Nevertheless, the sensitivity analysis in general confirms that nuclear power is fairly competitive from a long term perspective and should retain its role as one of the major electricity generation sources in the central region of Russia.

4. CONCLUSIONS

The outcome of the WASP study can be summarized as follows:

— The WASP application for the regional electricity system of the central region of Russia (the CPP) has confirmed that the WASP model allows complex electricity systems to be analysed on a sound methodological basis.

— Although WASP is a one-product model, some representation of the co-generation processes is possible.

— The major outcome of the WASP model — the optimal expansion plan for the regional electricity system — has been prepared and analysed; some of the most important sensitivities to a number of critical uncertainties have been calculated.

The following conclusions can be drawn from the results of the study:

(1) Before the year 2004, there will be no need for new electricity generation capacities because of the drop in demand in the 1990s, a certain lifetime margin of existing capacities, predetermined inputs of cogenerators and planned refurbishment/repowering measures.

(2) The study has confirmed that under the conditions of the economy in transition the projection of cost escalation factors is the key driving parameter for system development. This relates to all costs: capital, O&M and fuel costs. Elaboration of such projections with adequate consistency at both the regional level and the national level is an urgent task.

(3) Among the strategies investigated, the development based on gas fired technologies is found to be economically attractive for the region. However, when the possibility of accelerated price escalation for fossil fuels is taken into account, the structure of the optimal capacity mix confirms that nuclear power is fairly competitive in the long term perspective and should retain its role as one of the major electricity generation sources in the region.

In addition, concerning the applicability of the IAEA WASP model to the analysis of the Russian power system, the following points are noted:

- The new, enhanced version of WASP (WASP-III Plus) is an important step forward in the development of the program. Although the enhancements have been mostly technical, some of them, e.g. the possibility of considering ten types of fuel instead of four, are necessary for a realistic representation of such complex systems as the Russian one.
- The absence of cogeneration modelling remains a drawback of the WASP model. This drawback is essential for the Russian power pools with their large share of cogeneration units.
- At present, the structure of the optimal solution and some system costs can be calculated with WASP. However, it is not possible to use WASP for calculating the cost of generated electricity as a function of time for the system as a whole and in a unit-by-unit representation. This would be a useful enhancement of the model.
- The study has confirmed that WASP can be successfully used for regional investigations. However, interconnections play a large role in some of the Russian power pools as well as in the national system as a whole. In such cases, tools capable of modelling interconnections should be used instead of WASP or in combination with it.

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ELECTRICITY GENERATION ALTERNATIVES IN TURKEY WITH CONSIDERATION OF ENVIRONMENTAL IMPACTS

G. VAROL
Turkish Electricity Generation and Transmission Corporation

S. AKTÜRK
Turkish Atomic Energy Authority

Ankara, Turkey

Abstract

ELECTRICITY GENERATION ALTERNATIVES IN TURKEY WITH CONSIDERATION OF ENVIRONMENTAL IMPACTS.

The future expansion of the electricity generation system of Turkey was studied by using a two-phase approach. The first phase, the so-called Middle Term Generation Planning Study, covers the period 1994–1997. This study takes into consideration the electric energy generated by operating power plants, as well as that generated by plants under construction and by plants that have been approved for construction. Since difficulties will be encountered in meeting the demand with the existing power plants and with those under construction by the year 1996, the second phase of the study, the so-called Long Term Generation Expansion Planning Study, covering the period 1996–2010, was analysed by using the WASP III (Wien Automatic System Planning Package) generation investment optimization model. The demand forecasts used in both studies, which reflect social, economic and technical development policies in Turkey over the next 17 years, were derived by running the model of the analysis of energy demand (MAED). The objective of the second phase of the study is to find out the optimum expansion programme(s) satisfying the predicted electricity demand(s) over the planning period at minimum costs while meeting certain constraints on system reliability and number of plant additions per year. The overall economic criterion is the minimum discounted cost of expansion, including the following items: the investment costs of all plants added by the model, reduced by their respective salvage value at the time horizon; and the total operating costs of the system per year, including the fuel costs of thermal plants, the operation and maintenance costs of each plant, plus the cost of energy not served. The air pollution impacts of this electricity generation expansion plan on the environment were analysed with the IMPACTS module of ENPEP. In general, IMPACTS provides results for both controlled and uncontrolled emissions. Controlled emissions are those which can be expected with proper operation of existing and specified future pollution control equipment. Uncontrolled emissions would result from the operation of systems without any pollution control equipment.

1. PRESENT SITUATION OF THE ELECTRICITY SECTOR

1.1. Installed capacity and electricity production

The power system of Turkey has developed very rapidly during the last two decades. In connection with the fast development of the industrial sector, the high population growth rate and the significant migration of people from rural to urban areas, the peak load and the electric energy consumption have increased greatly from year to year.

The total installed capacity in Turkey, with an annual increase of 2.6%, was 20 857 MW by the end of 1994, with 53% from thermal power plants and 47% from hydropower plants.

In accordance with the increase in installed capacity, the electricity generation also increased and the energy demand was met with a sufficient reserve during the last decade. The total gross electricity production has grown at an annual rate of 6.0% and reached 78 260 GW·h in 1994.

1.2. Primary resources used for electricity production

The most important primary resources that are currently being utilized for electricity production are domestic hydro and lignite reserves. In recent years, imported natural gas also played an increasing role in power generation, in contrast to fuel oil whose share is steadily decreasing.

The total hydro potential for electricity generation is 122×10^9 kW·h/a, of which at present only 26.7% is being utilized for this purpose. By the end of 1995, with the commissioning of the hydropower plants in the construction stage, 31% of the total potential have been exploited.

The reserves of domestic lignite and hard coal can be used to produce about 120×10^9 kW·h/a. These lignite reserves are of low calorific value and have a large content of sulphur, moisture and ash. At present, the production capacity of our existing lignite fired power plants is about 36×10^9 kW·h/a, which is 30% of the total potential.

1.3. Environmental programmes for coal fired power plants

The main objective of previous development plans in Turkey was to supply continuous, safe and economic energy by utilization of domestic sources. However, today, environmental issues of power generation are also taken into consideration.

Over the past decade, the steady increase in SO_2 emissions from the Turkish power sector has raised growing public concern about the effect of air pollution on human health and on agriculture. Domestic lignite has a high sulphur content and/or a low calorific value when used in thermal power generation. Therefore, an environmental measure of considerable importance is the integration of flue-gas desulphurization (FGD) plants into thermal power stations.

In 1991, the first wet limestone FGD system in Turkey started operation at the Çayirhan power plant. Under the existing regulations and because of public pressure and the increasing enforcement capability of the Ministry of the Environment, SO_2 emission control technologies will have to be included in the design of future coal fired power plants.

Four FGD system projects have already been included in the investment programme. In accordance with the priorities and within the financial possibilities, FGD facilities for the rest of the existing thermal power plants will be included in the investment programme and will be realized in the near future.

1.4. Projections of the demand for electric energy and power in Turkey

During the last decade, electricity sales have increased by almost 9.2% p.a. on average, compared with an increase of 8.8% p.a. over the period 1973–1983. In 1993, the electricity supply amounted to some 59×10^9 kW·h — more than 2.4 times the value recorded in 1983. The average increase in the gross domestic product (GDP) during the last ten years was 5.1% p.a.

A study on the projected electric energy demand in Turkey was carried out using the MAED model. According to the results of this study, the electric energy demand, with an average annual growth rate of 8.0%, is expected to reach 87×10^9 kW·h by the year 1995, 130×10^9 kW·h by the year 2000 and 271×10^9 kW·h by the year 2010. A constant increase in the GDP of 6.0% p.a. over the planning period is assumed.

The corresponding peak demand is expected to reach 14 000 MW by the year 1995, 21 000 MW by the year 2000 and 43 000 MW by the year 2010.

2. STUDIES ON ELECTRICITY GENERATION EXPANSION PLANNING IN TURKEY

The future expansion of the electricity generation system of Turkey was studied by using a two-phase approach. The first phase, the so-called Middle Term Generation Planning Study, covers the period 1994–1997. This study takes into consideration the electric energy generated by operating power plants, as well as that generated by plants under construction and by plants that have been approved for construction. Since for this period the commissioning dates of new generating units had been determined, optimization of investments was not studied.

Because of the difficulties that will be encountered in meeting the demand with the existing power plants and with those under construction by the year 1996, the second phase of the study, the so-called Long Term Generation Expansion Planning Study, covering the period 1996–2010, was analysed by using the WASP III (Wien Automatic System Planning Package) model. The objective of this study was to find the optimum expansion programme that satisfies the predicted electricity demand over the planning period at minimum costs while meeting certain constraints on system reliability and the number of plant additions per year. The overall economic criterion is the minimum discounted cost of expansion, including the investment costs of all plants added by the model, reduced by their respective salvage value at the time horizon, and the total operating costs of the system per year, including the fuel costs of thermal plants, the operation and maintenance costs of each plant, plus the cost of energy not served.

2.1. Economic parameters and reliability constraints

The following criteria were used in the economic evaluation:

(a) Study period: 1993–2010.

(b) Planning period: 15 years, from 1996 to 2010.

(c) Reference year: The reference year for all cost discounting and escalation calculations is 1993.

(d) Calculation currency: All costs are expressed in US dollars (constant prices).

(e) Discount rate: A single discount rate of 8% was applied to all domestic and foreign capital investment and operating costs.

(f) Loading order: The economic loading order, based on the operating costs of the existing thermal generating units and the candidates for system expansion, was calculated by the WASP III program.

(g) Reserve margin: The planning reserve margin is defined as the ratio of the available system capacity to the peak load in the critical period and is usually expressed as a percentage of the peak load. In order to have full scope for optimization, the lower and upper limits of the reserve margin were taken to be very wide, exceeding the peak demand by 10% and 60%, respectively, to take into account and to simulate every possible configuration of the existing generating units and of the expansion candidates that could meet the system demand and the reliability requirements.

(h) Cost of energy not served: The cost of energy not served was calculated with the second-degree polynomial.

(i) Loss of load probability (LOLP): The LOLP expresses the fraction of time during which the available capacity of the system is insufficient to meet the electrical load. The upper limit for the LOLP reliability parameter was specified as 3% (10 days per year).

(j) Seasonal periods: The number of seasonal periods, used to account for the seasonal variations in demand, was taken to be four, and normalized load duration curves were used for each seasonal period.

(k) Hydrological conditions: The number of hydrological conditions was taken to be three; the probable percentages of these conditions are: average — 65%, wet — 20%, dry — 15%.

2.2. Existing and committed plants (fixed system)

In this study, the operational power plants, the power plants under construction and those which had been approved for construction were defined as a fixed system. The existing geothermal generation capacity of 15 MW was attributed to the existing hydropower plants.

Because of the limitation on the number of hydropower plants that could be handled by the model, the hydropower plants of the existing system were combined in groups and were studied as groups.

2.3. Candidate power plants evaluated during the planning period (1996–2010) (variable system)

The candidate power plants studied included those plants that will utilize the entire domestic lignite resources and the hydropower plants that are in the master plan or in the reconnaissance phase, i.e. 75% of the total hydroelectric potential; the power plants fired with imported coal; the power plants fired with imported natural gas, as well as the nuclear power plants.

In line with the policy objective to reduce oil consumption for power generation, no new oil or diesel fired thermal power plants were considered for long term planning.

Because of the large variance in the quality of the lignite resources of the country, the candidate lignite fired power plants were evaluated in three groups, based on the unit sizes and the quality of the coal used. Thus it became possible to define candidate lignite fired power plants individually and to compare them with each other in order to determine which resource should be exploited first.

In summary, according to the ratings of the units and the characteristics of the fuel, seven classes of thermal power plant, consisting of three types of lignite fired plant, one type of hard coal fired plant, one type of imported coal fired plant, one type of natural gas fired plant and one type of nuclear plant, were defined in the model.

The prices of domestic and imported fuel were kept constant over the planning period.

The number of candidate hydropower plants considered was 106. Since the model can handle only 60 projects, the candidate hydropower plants were evaluated in 44 groups. The major projects that were at the top of the priority ranking list were evaluated individually, while the others were grouped together, according to the regions and positions in the priority ranking list.

The 44 groups of hydropower plants were divided into two classes, under the headings HYDA and HYDB, i.e. the hydropower candidates were grouped together in two categories distinguished by their individual plant factor. Hydropower plants with a plant factor of less than 30% were classified as peak load plants (HYDA); the remaining ones were referenced as base load power plants (HYDB). Thus it was possible to compare peak hydropower plants with other hydropower plants and to use the model to select the types of hydropower plant needed. Within each group, a pre-set sequence of implementation of hydropower plants was determined, and the maximum amount of power, as well as the maximum and minimum amounts of energy for four periods and under three hydrological conditions were provided for running the VALORAGUA model.

2.4. Basic assumptions for the study

The most significant assumptions affecting the optimal composition of the electricity generation system are listed below.

2.4.1. Implementation constraints

Because of the possible limitation on the implementation capacities, the infrastructure facilities, the manpower and the financial resources during the construction of thermal and hydropower plants were taken into consideration; some constraints were imposed on the number of units that can be added to the system each year.

A maximum of two units of domestic lignite power plants were allowed to come on line at the same site in each year of the planning period. The same constraint was applied to the power plants using imported coal and natural gas in order to prevent a rise in the share of imported fuels in the generating system. However, because of the difficulties encountered in meeting the demand with this constraint, adding more than two units per year and site was allowed towards the end of the planning period.

The number of hydropower plants to be installed per year was limited, with an average energy generation of around 3000 GW·h/a for the whole planning period. Because the hydropower projects are not of a standard size, this constraint is not valid for all years.

2.4.2. Resource constraints

The WASP model does not allow resource constraints to be integrated into the optimization process. Constraints of such a kind have to be dealt with either indirectly or in an iterative way by analysing whether the expansion solution satisfies the constraints. Both methods were used in this study.

The import of natural gas for power generation was limited to 6×10^9 m^3/a until the year 1995, 8×10^9 m^3/a until the year 2000, 12×10^9 m^3/a until the year 2005 and 17×10^9 m^3/a until the year 2010.

The amount of imported coal was limited to 10 million t/a until the year 2000, 15 million t/a until the year 2005 and 20 million t/a until the year 2010. Diversification of resources was taken into account.

2.4.3. Environmental assumptions

The investment costs and the operation and maintenance costs were assumed to include the equipment necessary for reducing the pollution from operating solid fuel fired thermal power plants. In particular, the costs for pollution control devices using the wet limestone process and the selective catalytic reduction process were accounted for.

3. RESULTS OF THE LEAST COST EXPANSION STUDY

The characteristics of the electricity generation system according to the results of the least cost expansion study, in terms of installed capacity, reserve margin, LOLP and energy not served, are summarized in Table I.

The installed hydropower capacity amounts to approximately 38% of the total installed capacity by the year 2010, which represents an increase of approximately 2.4 times of the actual values. Because of the implementation constraints for hydropower plants, 66% of the hydro potential was used in this study.

The thermal capacity amounts to approximately 62% of the total installed capacity by the year 2010. This amount is 3.5 times the actual values. The contributions of lignite fired plants and fuel oil and diesel fired power plants to the overall installed capacity are reduced from 29.6% in 1993 to 24.7% in 2010 for lignite fired plants and from 9.4% in 1993 to 3.2% in 2010 for fuel oil fired plants.

Preference is given to the addition of natural gas fired, combined cycle power plants, to which 20.3% of the total installed capacity by the year 2010 are allocated. The share of these plants increases from 13.3% in 1993 to 20.3% in 2010 (Fig. 1). The share of power plants fired with imported coal will reach 10% by the year 2010.

The constraints on the annual addition of both hydropower plants and natural gas fired, combined cycle power plants are effective. If the constraints were relaxed, it would be preferable to increase the share of hydropower plants and gas fired power plants.

Two nuclear units of 1000 MW each, corresponding to 3.3% of the total capacity, are added by the end of the planning period.

TABLE I. SUMMARY OF THE LEAST COST EXPANSION STUDY

Capacity (MW)									Energy not served (GW·h)			
Year	Hydropower	Domestic coal	Natural gas	Imported coal	Nuclear	Total capacity	Peak load	Reserve margin (%)	Hydrological conditions[a]			LOLP (%)
									1	2	3	
1993	9 708	6 007	2 701	0	0	20 335	12 200	40	0	0	0	0.00
1994	10 093	5 803	2 671	0	0	20 492	12 915	37	0	0	5	0.10
1995	10 297	5 803	2 671	0	0	20 696	14 065	47	5	0	211	1.29
1996	10 969	6 304	3 351	0	0	20 549	15 235	48	10	0	322	1.66
1997	11 498	6 304	4 031	0	0	23 758	16 505	44	23	1	691	2.56
1998	11 498	7 434	4 711	0	0	25 568	17 880	43	24	1	287	1.91
1999	11 498	7 734	6 071	0	0	27 228	19 375	41	55	3	368	2.37
2000	12 537	8 714	6 071	0	0	29 247	20 990	39	57	2	552	2.89
2001	13 836	9 394	6 751	0	0	31 906	22 610	41	37	1	402	2.19
2002	15 416	9 734	7 431	0	0	34 506	24 360	42	38	1	912	2.73
2003	16 503	10 414	8 111	0	0	36 953	26 240	41	44	1	953	2.78
2004	18 097	10 904	8 791	0	0	39 717	28 260	41	46	1	1171	2.90
2005	18 617	11 054	8 791	1000	1000	42 387	30 445	39	56	1	887	2.81
2006	19 067	11 734	9 471	2000	1000	45 197	32 710	38	72	3	656	2.73

	Capacity (MW)								Energy not served (GW·h)				
Year	Hydropower	Domestic coal	Natural gas	Imported coal	Nuclear	Total capacity	Peak load	Reserve margin (%)	Hydrological conditions[a]			LOLP (%)
									1	2	3	
2007	19 519	12 564	10 151	3000	1000	48 159	35 145	37	91	4	759	2.99
2008	19 713	13 014	10 831	4000	2000	51 483	37 760	36	100	5	724	2.94
2009	21 607	13 654	11 511	5000	2000	55 697	40 570	37	92	5	722	2.79
2010	23 064	14 854	12 191	6000	2000	60 034	43 590	38	86	6	725	2.68
Share in 2010 (%)	38.4	24.7	20.3	10.0	3.3	100						

[a] Hydrological conditions: 1 — average (65%), 2 — wet (20%), 3 — dry (15%).

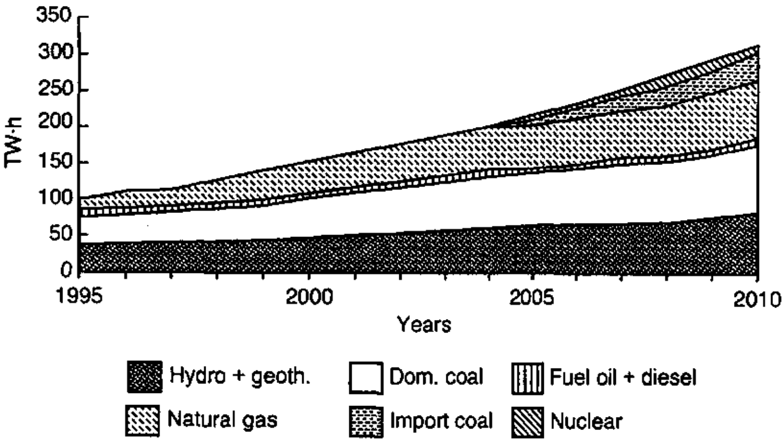

FIG. 1. Development of electricity generation.

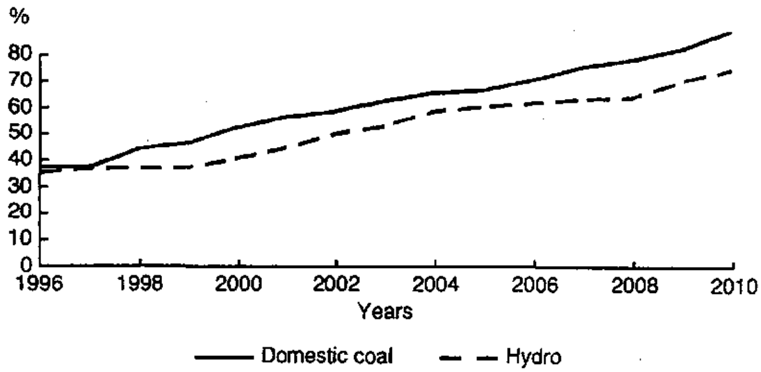

FIG. 2. Utilization of primary resources.

By the end of the planning period, 79% of the total potential of domestic lignite and hard coal will have been exploited (Fig. 2). As a result, by the year 2010, the number of thermal units added to the system consists of 14 units of natural gas fired, combined cycle power plants with 680 MW each, 12 units of plants with imported coal (500 MW each), 33 units of lignite power plants and 2 nuclear power plants (1000 MW each).

The hydropower plants operate with a load factor of approximately 40% in average years and a load factor of approximately 25% in dry years, while the lignite and coal fired power plants operate with load factors that exceed 70% at all times.

Comparing the respective fuel shares by the year 2010, the contribution of thermal power plants increases over the planning period at the expense of hydropower generation.

The reserve margin is considerably higher (48%) at the beginning of the planning period, but drops to 36% at the end of this period. The LOLP changes from 6 d/a to 10 d/a over the planning period. The expected proportion of energy not served varies between 0.0001 and 0.0004 of the demand in normal hydrological conditions and between 0.003 and 0.007 of the demand in dry hydrological conditions.

The total net present value (NPV) of the investments, including interest during construction and operating costs in the planning period, based on a discount rate of 8%, is 32×10^9 US \$. The NPV is referenced to the year 1993. The costs are expressed in 1993 constant US dollars.

Comparison of the composition of costs based on the NPV reveals that the share of the construction costs is 45% of the total costs. The total operating costs increase to some 23×10^9 US \$ by the end of the planning period.

4. SENSITIVITY ANALYSES

Since the number of natural gas fired power plants in the investment plan is high throughout the planning period, sensitivity analyses were carried out to test the sensitivity of limited gas supply, investment cost and fuel cost.

4.1. Sensitivity analysis of limited gas supply

In this analysis, the supply of natural gas for power generation was limited to 6×10^9 m^3/a. It was assumed that there will be no new additional purchasing agreements for gas.

As a result of this sensitivity analysis, only three new natural gas fired power plants will be added to the generating system between 1995 and 2010. All of the lignite and hard coal power plants defined as potential candidates, with a total installed capacity of 12 380 MW, will be in use by the year 2010.

4.2. Sensitivity analysis of the investment cost for natural gas fired power plants

The investment cost for natural gas fired power plants was increased by 75% compared with the cost used in the reference case. The total number of units that have to be added to the system during the planning period remained the same as in the reference case, but the commissioning dates of natural gas fired power plants were delayed by one or two years compared with the reference case.

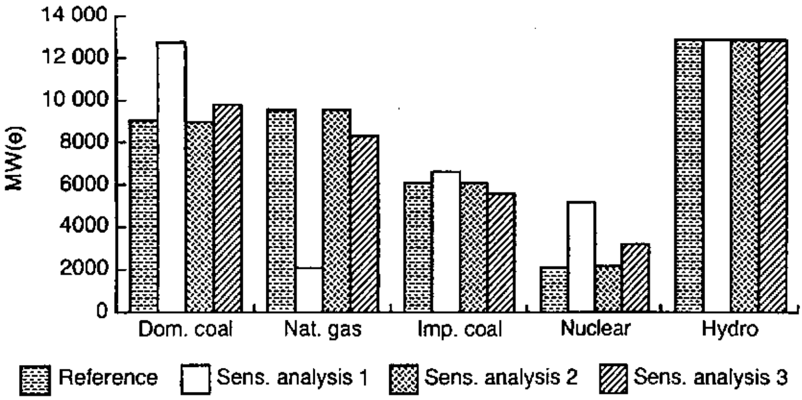

FIG. 3. Comparison of the sensitivity analyses with the reference case.

4.3. Sensitivity analysis of the price of natural gas

It was found that an increase in the natural gas price by 75% compared with the price used in the reference case had an influence on the result of the analysis. This cost increase led to a delay in the commissioning dates of natural gas fired power plants. As a result, 12 natural gas fired power plants instead of 14 will be commissioned by the end of the planning period. The number of lignite and nuclear power plants will increase accordingly.

A comparison of the sensitivity analyses with the reference case is given in Fig. 3.

5. AIR POLLUTION IMPACTS OF THE ENERGY GENERATION EXPANSION PLAN

A regulation on the protection of the air quality in order to control all kinds of emissions (soot, smoke, particulates) and to prevent adverse impacts of air pollution was issued in November 1986. The operation of most thermal power plants is subject to the restrictions given in this regulation.

At present, 32% of the total electricity production in Turkey depends to a considerable extent on solid fossil fuels. As a consequence of the characteristics of Turkish lignites, i.e. low calorific value, high ash and sulphur contents, the flue-gases emitted from power stations have high concentrations of SO_2 and dust.

It is intended to take a number of protection measures for thermal power plants to be constructed and to provide old plants with the necessary emission control equipment in order to meet the limit on emissions set in the regulations.

All lignite fired power plants were equipped with electrostatic precipitators (ESPs) of different efficiencies, depending on the technology applied. Satisfactory particulate emission control was achieved in power plants with an electrofilter efficiency of 99.4–99.82%. However, the efficiency of the ESPs in some of the power plants was insufficient and had to be improved in order to operate according to valid legislation.

Because of the high investment costs, simultaneous integration of FGD systems into all lignite fired power plants is far beyond Turkey's financial capabilities. A study was carried out to determine the priorities among all power plants, taking into account the location of the plants and the conditions in the surroundings, such as the population density, agriculture, forestry, tourism potential and public opposition.

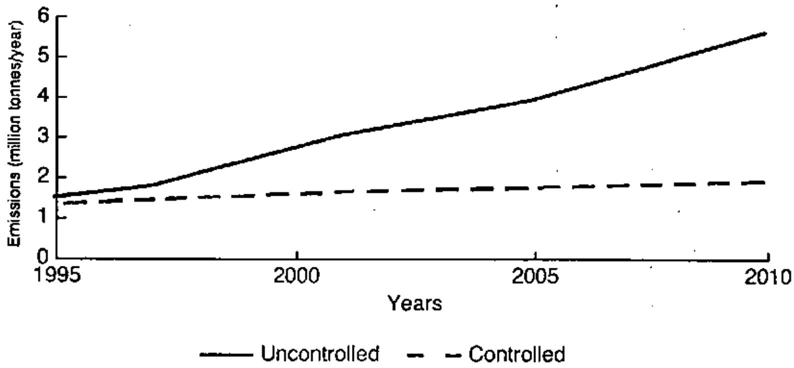

FIG. 4. Results for SO_2 emissions for the reference case.

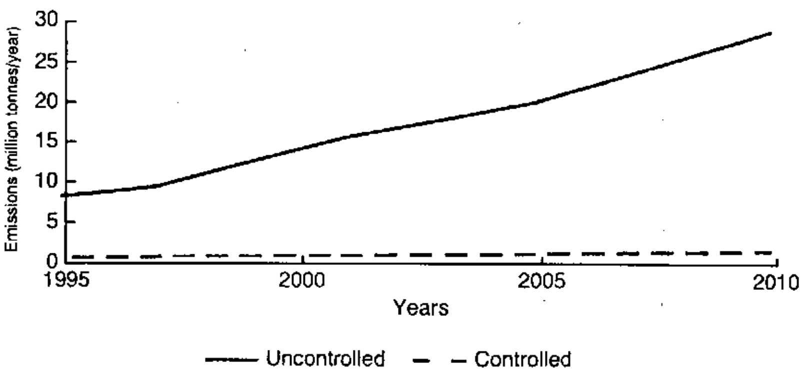

FIG. 5. Results for particulate emissions for the reference case.

As a consequence, power plants having SO_2 emissions higher than the emission values specified in the regulation are being retrofitted with FGD systems according to priority.

Because of the fusion temperatures that can be achieved with Turkish lignites of low ash content, the combustion chamber temperatures in the boilers and consequently the formation of NO_x are kept low. Furthermore, the tangential firing method adopted in most of the lignite fired plants in Turkey is effective in achieving proper combustion conditions. In general, the NO_x emission values are lower than the limits specified in the related legislation.

The air pollution impacts of the Turkish energy generation expansion plan on the environment were analysed with the IMPACTS module of ENPEP. In general, IMPACTS provides results for both controlled and uncontrolled emissions. Controlled emissions are those which can be expected with proper operation of existing and specified future pollution control equipment. Uncontrolled emissions would result from the operation of systems without any pollution control equipment. The results for the reference case are shown in Fig. 4 for SO_2 emissions and in Fig. 5 for particulate emissions.

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COMPARATIVE ASSESSMENT OF ENERGY SOURCES FOR ELECTRICITY GENERATION IN SLOVAKIA

J. BALAJKA, J. PESCHL, J. JUDÁK
Profing Company Limited,
Bratislava, Slovakia

Abstract

COMPARATIVE ASSESSMENT OF ENERGY SOURCES FOR ELECTRICITY GENERATION IN SLOVAKIA.

The inter-agency joint project on databases and methodologies for comparative assessment of different energy sources for electricity generation (DECADES), managed by the IAEA, focuses on the comparison of databases and modelling methods for electricity generating systems of different countries. One of the main targets of the project is the assessment of the environmental impacts of electricity generating systems. The work of the Slovakian group participating in the DECADES project focused on the following: (1) Collecting information on the technical and economic characteristics of electricity generation chains operating or expected to be implemented in Slovakia; and collecting data on emissions, burdens and residuals from these chains, as well as establishing a Slovakian database using the computer structure of the DECADES reference technology database (RTDB). (2) Reviewing the present environmental protection legislation in Slovakia and assessing its impacts on the choice of an electricity generation mix. (3) Assessing the potential impacts of ratifying the Second Sulphur Protocol and/or the Framework Convention on Climate Change on the electricity policy of Slovakia. In particular, the role of nuclear power in facilitating compliance with these stringent environmental regulations has been assessed.

1. INTRODUCTION

The inter-agency joint project on databases and methodologies for comparative assessment of different energy sources for electricity generation (DECADES), managed by the IAEA, focuses on the comparison of databases and modelling methods for electricity generating systems of different countries. One of the main targets of the project is the assessment of the environmental impacts of electricity generating systems. This paper comprises the main results obtained by the Slovakian group participating in the DECADES project. Our work focused mainly on the collection of information on the technical and economic characteristics of electricity generation chains. Operational power plants were assessed as well as new units that may be implemented in Slovakia. Strong emphasis was placed on the environmental impact of present and new power plants. The main target was the establishment of

TABLE I. ELECTRICITY GENERATION IN THERMAL POWER PLANTS AND COGENERATION PLANTS

Technical characteristics of electricity generation technologies

Installations[a]	Technology			Fuel
	Type	Sub-type	Facility	Type
Solid fuels				
Steam coal combustion				
PP EVO 1	PC	PCWBB	6 × 305	SSCS
Pub. COG TEKO	PC	PCWBB	108.8	SSCS
Ind. COG VSŽ	PC	PCWBB	136.9	SSCS
Lignite combustion				
PP ENO A	PC	PCDBB	10 × 81.4	SBCP
PP ENO B	PC	PCDBB	4 × 273.8	SBCP
Pub. COG Žilina	PC	PCDBB	53.1	SBCP1
Pub. COG Martin	CGO	GFMOV	58.15	SBCP2
Pub. COG Zvolen	CGO	PCDBB	13.32	SBCP3
Ind. COG JCP	PC	PCDBB	92.5	SBCP0
Ind. COG CHEMKO	CGO	PCDBB	2.3	SBCP0
Ind. COG CHEMEZ	CGO	PCDBB	17.76	SBCP0
Ind. COG Bukóza	FB	PCDBB	111	SBCP0
Ind. COG ZSNP	PC	GFMOV	55.5	SBCP0
Ind. COG PS	CGO	GFUOF	4.44	SBCP0
Ind. COG ZTS	CGO	PCDBB	11.84	SBCP0
Gaseous fuels				
PP EVO 2	CGO	CGO-cc	6 × 330	GNG
Pub. COG ZSE tp1	CGO	CGO-oil	33.6	GNG
Pub. COG ZSE tp2	CGO	CGO-cc	52	GNG
Pub. COG ZSE tp3	CGO	CGO-gas	3 × 19.5	GNG
Pub. COG ZSE Západ	CGO	CGO-oil	104.9	GNG
Pub. COG ZSE Trnava	GF	GFG-cc	20.9	GNG
Liquid fuels				
Ind. COG Slovnaft	CGO	CGO-oil	59.2	LHFO
Ind. COG Slov. Hedváb	CGO	CGO-cc	+2 × 11.1 + 2	LHFO
Ind. COG Majtex	CGO	CGO-cc	18.5	LHFO

[a] PP — power plant, Pub. COG — public cogeneration unit, Ind. COG — industrial cogeneration unit.

Output capacity (MW)			Net eff.	Heat rate (kcal/kW·h)				Supply HR[b]
Gross	Net	Min.	(%)	Full load	Min. load	Increment	Calc. 1990	(GJ/GJ)
660.0	600.0	55.0	30.3	2986	3105	2818	2840	
121.0			64.7	2030	2150	1767	1328	1.19
189.0			42.6				2017	1.240
108.8		5.0	27.1	3344	3583	3153	3172	
440.0	400.0	55.0	29.3	3224	3344	2866	2933	
49.0			72.0				1194	1.270
47.5			63.9				1345	1.310
34.8			67.9				1266	1.280
50.0			45.7				1881	1.370
40.0			64.3				1338	1.350
24.0			41.9				2052	1.290
35.0			73.5				1170	1.270
37.0			65.5				1314	1.200
12.0			45.8				1878	1.410
12.4			24.8				3473	1.230
660.0	600.0	55.0	33.8	2747	2986	2532	2544	
14.4			76.8				1120	1.190
20.0			77.9				1103	1.190
6.0			76.9				1118	1.190
25.0			81.3				1058	1.160
12.0			25.0				3439	1.220
107.0			53.8				1598	1.200
6.1			30.9				2779	1.120
6.4			68.3				1259	1.260

[b] Supply HR = rate of heat supplied from cogeneration units.

a Slovakian database, using the computer structure of the DECADES reference technology database (RTDB). The paper gives a summary of the main technical and environmental characteristics of electricity generating plants. Although the DECADES RTDB structure does not consider electricity generation chains with cogeneration units, we discuss the possibility of their implementation and make proposals regarding the calculation of the emission factor.

2. COUNTRY SPECIFIC DATABASE

The available data of electricity generating systems have been collected from utilities and industrial sources. With regard to the actual situation in Slovakia, difficulties must be overcome in order to apply the structure of the RTDB to the specific conditions of the country. Nevertheless, the collected data make it possible to model the electricity system in Slovakia with IAEA models (WASP and ENPEP). Table I summarizes the main technical data of thermal power plants and cogeneration plants used in Slovakia for electricity production. The electricity heat rate as well as the rate of heat supplied from cogeneration units is included. These values are used for the calculation of the emission factor. Tables II and III summarize the main technical data of nuclear power plants and of hydropower plants, respectively.

The main problems in connection with the preparation of the tables are: (1) *The lack of economic data.* The available data cannot be compared with those for plants in western countries because of the different historical and economic situation. These data are changing drastically because of the ongoing transformation process. (2) *The large share of cogeneration units.* There are only few public thermal power plants in the electricity generating system and the number of cogeneration units is large. Cogeneration is also applied in public power plants and data connected with simultaneous heat production should be incorporated in the country specific database (CSDB).

In Slovakia, several types of boiler are used for both electricity generation and heat and electricity cogeneration. Table IV summarizes the types of boiler used.

3. CALCULATION OF EMISSION FACTORS

In the DECADES RTDB structure, the emission factor has to be expressed as the amount of pollutant per kilowatt-hour of electricity produced. In order to achieve good transparency, the algorithm used in this calculation is described together with the input data. Other problems in connection with the Slovakian electricity generating system, which complicate the consistency of the data with the required CSDB structure, are summarized as follows.

TABLE II. ELECTRICITY GENERATION IN NUCLEAR POWER PLANTS

Technical characteristics of electricity generation technologies

Technology			Status of development		Output capacity (MW(e))			Net eff. (%)
Type	Sub-type	Facility		Year	Gross	Net	Min.	
WWER-440	2 × 440 MW	EBO 1	M	1978	1760	1632	200	31.0
WWER-440	2 × 440 MW	EBO 2	M	1984	1760	1632	200	31.0
WWER-440	2 × 440 MW	EMO	C	1997	880	820	200	31.5

Technology			Heat rate (kcal·kW·h)			Possible equivalent full power (h/a)	Capacity factor (%)	Scheduled maintenance (d/a)	Forced outage (%)
Type	Sub-type	Facility	Full load	Min. load	Increment				
WWER-440	2 × 440 MW	EBO 1	2699.0	2866.2	2531.8	6850	78.1	50	7.0
WWER-440	2 × 440 MW	EBO 2	2699.0	2866.2	2531.8	6850	78.1	50	7.0
WWER-440	2 × 440 MW	EMO	2627.3	2746.7	2412.3	6850	78.1	50	5.0

TABLE III. ELECTRICITY GENERATION IN HYDROPOWER PLANTS
Technical characteristics of electricity generation technologies

Technology		Commissioning	Output capacity (MW(e))			Net eff.	Possible equivalent
Type	Facility	(Year)	Gross	Net	Min.	(%)	(h/a)
Existing units (1990)							
Run-of-river hydro			23			86.0	2000
Hydro with storage			716			86.0	2600
Pumped storage			915			74.0	700
Planned units							
Run-of-river hydro	Gabčikovo, Čuňovo	1993	544			86.0	3000
Hydro with storage	Žilina, Sered', Strečno	2000	146			86.0	2500

TABLE IV. CONSIDERED TYPES OF COMBUSTION TECHNIQUES

Type of combustion chamber	Abbreviation	Code
Combined combustion oil/gas	CC-oil/gas	CGO-cc
Combustion of gaseous fuels	CGO-gas	CGO-gas
Combustion of oil fuels	CGO-oil	CGO-oil
Atmospheric fluidized bed combustion, bubbling	AFBCB	FBCAB
Atmospheric fluidized bed combustion, circulating	AFBCC	FBCAC
Pressurized fluidized bed combustion, bubbling	PFBCB	FBCPB
Pressurized fluidized bed combustion, circulating	PFBCC	FBCPC
Combined combustion gas/grate coal firing	CCGF-gas	GFG-cc
Grate firing — moving	GF-moving	GFMOV
Combined combustion oil/grate coal firing	CCGF-oil	GFO-cc
Combined combustion pulverized/grate coal firing	CCGF/PF	GFPC-cc
Grate firing — spreaderstoker	GF-spreaderstoker	GFSPR
Grate firing — stationary	GF-stationary	GFSTA
Grate firing — under/over feed	GF-u/o-fed	GFUOF
Pulverized coal boiler/cyclone	PCBF-cycl	PCCYC
Pulverized coal boiler/dry bottom	PCBF-DBB	PCDBB
Combined combustion gas/pulverized coal	CCDBB-gas	PCG-cc
Combined combustion oil/pulverized coal	CCDBB-oil	PCO-cc
Pulverized coal boiler/wet bottom	PCBF/WBB	PCWBB

(a) Usually, a number of fuel types are used in one unit, both simultaneously and alternatively, in winter and in summer. In the public cogeneration plant TEKO, for example, in winter, hard coal is combusted together with gas, which is used to stabilize the combustion process. In summer, only gas is used. There are many cogeneration units where gas is combusted in summer and oil in winter. This means that one unit could be incorporated in several DECADES chains (solid/gas, gas/oil, etc.).

(b) In the CSDB structure, cogeneration is not considered. This problem could be solved by including the additional values in the database, as shown in Tables I–III.

(c) The CSDB structure considers the following simple system:

fuel → boiler → turbine/generator → electricity network.

TABLE V. EMISSION FACTORS FOR GASEOUS POLLUTANTS

Code	g NO_x/GJ_{fuel}	g CO/GJ_{fuel}	g VOC/GJ_{fuel}
Lignite combustion			
CGO-gas	290	50	4
FLUID	230	120	15
GFMOV	190	810	6
GFO-cc	220	500	6
GFSPR	180	930	6
GFSTA	190	350	6
GFUOF	220	500	6
PCDBB	290	50	4
Steam coal combustion			
CGO-gas	140	30	4
FLUID	110	60	15
GFMOV	130	550	6
GFO-cc	120	240	6
GFSPR	100	560	6
GFSTA	130	250	6
GFUOF	120	240	6
PCCYC	1330	30	2
PCDBB	140	30	4
PCWBB	580	30	2
Oil and gas combustion			
OIL	230	70	4
NG	80	90	5

In some facilities there are several boilers for combustion of different fuels; these boilers are connected through the common superheated steam pipe to one or several turbines. The system could become more complicated by the use of different types of turbine with different heat rates. It is difficult to determine whether the system should be included in the solid, the liquid or the gaseous fuel source chain. Nevertheless, the latter systems are mainly used in industrial facilities, which do not play an important role in the national electricity generating system.

TABLE VI. EMISSION FACTORS FOR PARTICULATES

Code	EF [kg/t_{fuel}]
Lignite combustion	
CGO-gas	8.5
FLUID	3
GFMOV	1.9
GFO-cc	1.9
GFSPR	5
GFSTA	1
GFUOF	3.5
PCDBB	8.5
Steam coal combustion	
CGO-gas	8.5
FLUID	3
GFMOV	1.7
GFO-cc	1.7
GFSPR	5
GFSTA	1
GFUOF	3.5
PCCYC	1.5
PCDBB	8.5
PCWBB	8.5
Oil and gas combustion	
OIL	2.91
NG	0

In order to solve the problems in connection with the emission factors, we have prepared two sets of emission factors (Tables V and VI), both for electricity and heat production.

3.1. Emission factors for operating power plants and cogeneration plants

A simplified model for the use of one type of fuel is considered; this is convenient for the RTDB energy chain structure. The fuel with the highest share in

TABLE VII. ELECTRICITY GENERATION
Environmental characteristics of electricity generation technologies

Technology[a]			Airborne emissions (electricity supply) (g/kW·h)					
Type		Facility	Partic.	CO_2	NO_x	CO	SO_2	VOC
Pulverized coal furnace								
PCWBB	REZZO	PP EVO 1	8:306	1114	7.19	0.24	18.71	0.073
	EM. limit		0.439	1114	4.83	0.24	2.82	0.073
PCWBB	REZZO	Ind. COG VSŽ	3.943	688	2.38	0.18	8.90	0.038
	EM. limit		0.312	688	2.38	0.18	2.00	0.038
PCDBB	REZZO	PP ENO A	3.212	1250	7.84	0.65	44.30	0.198
	EM. limit		0.336	893	1.35	0.65	1.35	0.198
PCDBB	REZZO	PP ENO B	3.212	1162	7.77	0.64	43.87	0.194
	EM. limit		0.486	1162	2.67	0.64	8.26	0.194
PCDBB	REZZO	Pub. COG Žilina	1.641	475	3.86	0.21	8.42	0.064
	EM. limit		0.309	475	1.70	0.21	1.36	0.064
PCDBB	REZZO	Pub. COG Zvolen	1.654	459	1.10	0.20	5.73	0.105
	EM. limit		0.210	459	1.10	0.20	0.97	0.105
PCDBB	REZZO	Ind. COG JCP	2.586	718	3.61	0.30	17.74	0.110
	EM. limit		0.348	718	1.92	0.30	1.52	0.110
PCDBB	REZZO	Ind. COG CHEMKO	1.064	433	2.13	0.16	5.15	0.048
	EM. limit		0.217	433	1.19	0.16	0.95	0.048
PCDBB	REZZO	Ind. COG Bukóza	0.815	454	2.82	2.09	13.85	0.671
	EM. limit		0.217	454	1.19	2.09	0.95	0.671
Grate firing combustion								
GFMOV	REZZO	Ind. COG CHEMEZ	4.739	749	2.61	0.37	11.12	0.170
	EM. limit		0.380	749	2.09	0.37	1.66	0.170
GFUOF	REZZO	Ind. COG PS	48.409	712	2.02	0.62	17.68	0.307
	EM. limit		0.348	712	1.91	0.62	1.52	0.307
GFMOV	REZZO	Pub. COG Martin	7.682	471	1.67	0.21	7.63	0.084
	EM. limit		0.207	471	1.14	0.21	0.66	0.084

[a] REZZO = emission factors calculated on the basis of data from the National Inventory System, REZZO.

EM. limit = emission factors calculated on the basis of new emission concentration limits.

TABLE VII (cont.)

Technology[a]			Airborne emissions (heat supply) (kg/GJ)					
Type		Facility	Partic.	CO_2	NO_x	CO	SO_2	VOC
Pulverized coal furnace								
PCWBB	REZZO	PP EVO 1						
	EM. limit							
PCWBB	REZZO	Ind. COG VSŽ	0.579	101	0.350	0.027	1.307	0.006
	EM. limit		0.046	101	0.350	0.027	0.294	0.006
PCDBB	REZZO	PP ENO A						
	EM. limit							
PCDBB	REZZO	PP ENO B						
	EM. limit							
PCDBB	REZZO	Pub. COG Žilina	0.417	121	0.981	0.055	2.139	0.016
	EM. limit		0.05	121	0.26	0.055	0.211	0.016
PCDBB	REZZO	Pub. COG Zvolen	0.400	111	0.265	0.048	1.383	0.025
	EM. limit		0.05	111	0.27	0.048	0.235	0.025
PCDBB	REZZO	Ind. COG JCP	0.450	125	0.629	0.052	3.090	0.019
	EM. limit		0.06	125	0.33	0.052	0.265	0.019
PCDBB	REZZO	Ind. COG CHEMKO	0.256	104	0.511	0.038	1.239	0.011
	EM. limit		0.056	104	0.309	0.038	0.246	0.011
PCDBB	REZZO	Ind. COG Bukóza	0.294	164	1.015	0.753	4.993	0.242
	EM. limit		0.056	164	0.309	0.753	0.246	0.242
Grate firing combustion								
GFMOV	REZZO	Ind. COG CHEMEZ	0.710	112	0.392	0.056	1.668	0.025
	EM. limit		0.057	112	0.314	0.056	0.249	0.025
GFUOF	REZZO	Ind. COG PS	8.681	128	0.363	0.111	3.171	0.055
	EM. limit		0.062	165	0.343	0.855	0.273	0.055
GFMOV	REZZO	Pub. COG Martin	1.787	110	0.388	0.049	1.775	0.019
	EM. limit		0.048	110	0.265	0.049	0.154	0.019

the total thermal input is selected as reference fuel. In the case of public thermal power plants the share of solid fuels is assumed to be >95%, and this simplification does not lead to large errors. In the case of cogeneration units the situation is more complicated. In the public cogeneration plant Žilina, the share of natural gas in lignite combustion can reach 30%. However, with other fuels, this value does not exceed 10%. The algorithms used for the calculation of individual emission factors are presented below.

3.1.1. Carbon dioxide emission factor

$$[\text{kg } CO_2/GJ_{\text{fuel}}] = \frac{C\ [\%]\ 440/12\ (100 - W\ [\%] - A\ [\%])}{100\ \text{LHV}\ [GJ/t]}$$

where LHV is the lower heating value.

$$[\text{g } CO_2/\text{kW}\cdot\text{h}] = [\text{kg } CO_2/GJ_{\text{fuel}}] \times [GJ_{\text{fuel}}/\text{MW}\cdot\text{h}]$$

$$[\text{kg } CO_2/GJ_{\text{heat}}] = [\text{kg } CO_2/GJ_{\text{fuel}}] \times [GJ_{\text{fuel}}/GJ_{\text{heat}}]$$

3.1.2. Sulphur dioxide emission factor

$$[\text{kg } SO_2/GJ_{\text{fuel}}] = \frac{S\ [\%]\ 19\ (100 - W\ [\%] - A\ [\%])}{100\ \text{LHV}\ [GJ/t]}$$

$$[\text{g } SO_2/\text{kW}\cdot\text{h}] = [\text{kg } SO_2/GJ_{\text{fuel}}] \times [GJ_{\text{fuel}}/\text{MW}\cdot\text{h}]$$

$$[\text{kg } SO_2/GJ_{\text{heat}}] = [\text{kg } SO_2/GJ_{\text{fuel}}] \times [GJ_{\text{fuel}}/GJ_{\text{heat}}]$$

The content of carbon [%] and sulphur [%] is considered on water and ash free bases, as used in the RTDB structure.

3.1.3. Emission factors of NO_x, CO and volatile organic compounds (VOC)

On the basis of measured and published values, the new emission factors have been used for the emission calculation [1]. The values for the electricity generating sources are summarized in Table VII. The emission factors for consumed fuel are used for the calculation of emission factors for produced electricity and supplied heat units:

$$[\text{g } NO_x/\text{kW}\cdot\text{h}] = 10^{-3} \times [\text{g } NO_x/GJ_{\text{fuel}}] \times [GJ_{\text{fuel}}/\text{MW}\cdot\text{h}]$$

$$[\text{kg } NO_x/GJ_{\text{heat}}] = 10^{-3} \times [\text{g } NO_x/GJ_{\text{fuel}}] \times [GJ_{\text{fuel}}/GJ_{\text{heat}}]$$

$$[\text{g CO/kW}\cdot\text{h}] = 10^{-3} \times [\text{g CO/GJ}_{\text{fuel}}] \times [\text{GJ}_{\text{fuel}}/\text{MW}\cdot\text{h}]$$

$$[\text{kg CO/GJ}_{\text{heat}}] = 10^{-3} \times [\text{g CO/GJ}_{\text{fuel}}] \times [\text{GJ}_{\text{fuel}}/\text{GJ}_{\text{heat}}]$$

$$[\text{g VOC/kW}\cdot\text{h}] = 10^{-3} \times [\text{g VOC/GJ}_{\text{fuel}}] \times [\text{GJ}_{\text{fuel}}/\text{MW}\cdot\text{h}]$$

$$[\text{kg VOC/GJ}_{\text{heat}}] = 10^{-3} \times [\text{g VOC/GJ}_{\text{fuel}}] \times [\text{GJ}_{\text{fuel}}/\text{GJ}_{\text{heat}}]$$

3.1.4. Emission factors for particulates

The emission factors (EF) for particulates (part.) have been calculated using the same values as are used in the National Inventory Systems [2]. These data are expressed for individual fuels and types of combustion [kg/t_{fuel}]. The emission factors for fuels are calculated in the National Inventory System (REZZO) as follows:

$$[\text{kg part./GJ}_{\text{fuel}}] = \text{EF A [\%]/LHV [GJ/t]}$$

The required emission factors are calculated by using the heat rates of electricity and of supplied heat:

$$[\text{g part./kW}\cdot\text{h}] = [\text{kg part./GJ}_{\text{fuel}}] \times [\text{GJ}_{\text{fuel}}/\text{MW}\cdot\text{h}]$$

$$[\text{kg part./GJ}_{\text{heat}}] = [\text{kg part./GJ}_{\text{fuel}}] \times [\text{GJ}_{\text{fuel}}/\text{GJ}_{\text{heat}}]$$

3.2. Emission factors including the impact of environmental legislation

These factors represent the emission factors for individual energy sources after the year 2000, when all new emission concentration limits will be obligatory. The implementation of abatement technologies is considered together with the installation of combined cycles. The algorithms are presented below.

3.2.1. Flue-gas volume

In order to calculate the emission factor per kilowatt-hour and gigajoule for supplied heat, the flue-gas volume was calculated from the ultimate analysis values:

$$\text{Vol. [Nm}^3\text{/MJ]} = \frac{(8.931\ C[\%] + 21.194\ (H[\%] - O[\%]/8) + 0.8\ N[\%] + 3.349\ S[\%]}{\text{LHV [GJ/t]} \times 100} \times \frac{(100 - W[\%] - A[\%])}{100}$$

The emission concentration limits are expressed as the oxygen concentration ($O_{2,ref}$) in flue gases. These limits are 6% in the case of solid fuels and 3% in the case of liquid and gaseous fuels. The default gas volume (DVol.) is therefore calculated for these fuels:

$$\text{DVol. [Nm}^3\text{/MJ]} = \frac{21}{21 - O_{2,ref}[\%]}$$

3.2.2. Sulphur dioxide emission factor

For fluidized bed combustion, the default SO_2 concentration is 400 mg/Nm^3. In the case of wet flue-gas desulphurization (FGD), the default SO_2 concentration is 500 mg/Nm^3. In the case of dry FGD, the default efficiency of the process is 90% and this value is used for the calculation of the emission limit [kg SO_2/GJ_{fuel}] from the material balance. If for an individual source no abatement technology has been determined, it is proposed to use an SO_2 concentration emission limit of 1700 mg/Nm^3.

The emission limit [kg SO_2/GJ_{fuel}] obtained from the concentration values is calculated as follows:

$$[\text{kg } SO_2/GJ_{fuel}] = \frac{[\text{mg } SO_2/\text{Nm}^3] \times \text{DVol. [Nm}^3\text{/MJ]}}{1000}$$

$$[\text{g } SO_2/\text{kW}\cdot\text{h}] = [\text{kg } SO_2/GJ_{fuel}] \times [GJ_{fuel}/\text{MW}\cdot\text{h}]$$

$$[\text{kg } SO_2/GJ_{heat}] = [\text{kg } SO_2/GJ_{fuel}] \times [GJ_{fuel}/GJ_{heat}]$$

3.2.3. Emission factors for NO_x, CO, VOC and particulates

Using the emission concentration limits, the same way of calculating the emission factor has been used for NO_x, CO and particulates. In the case of fluidized bed combustion (FBC), the default NO_x concentration is 400 mg NO_x/Nm^3. In the case of the combined cycle, the default concentrations are 400 mg NO_x/Nm^3 and 100 mg CO/Nm^3. The VOC emission factors are calculated in the same way as in the case of the simplified model (Section 3.1).

4. IMPACT OF INTERNATIONAL AGREEMENTS

The Second Sulphur Protocol and the Framework Convention on Climate Change (FCCC) represent international agreements that had an impact on the electricity generating system in Slovakia. The new emission concentration limits for SO_2 will incorporate the systems in regulation 88/609/EEC. According to the new proposal of the Ministry of the Environment, the emission concentration limit for boilers with a thermal capacity of > 140 MW(th) will be determined as follows:

$$[\text{mg } SO_2/\text{Nm}^3] = 2400 \text{ MW(th)} - 5$$

For the existing energy sources, this limit will be obligatory after the year 2005. This new regulation will affect mainly the following facilities [3]: EVO 1, with two retro-fitted units with dry FGD. Wet FGD in ENO B will achieve the required value, and for the new installed FBC unit this regulation is not obligatory.

Slovakia has signed the FCCC in 1994 and is obliged to stabilize CO_2 emissions by the year 2000 at the 1990 level. It is considered a national target to decrease CO_2 emissions by 20% by the year 2005 to the 1988 level [4]. If the nuclear power plant Mochovce is not in operation by the year 2000 because of a delay in construction, the equivalent electricity demand will be covered by the existing thermal power and cogeneration plants, and the national target will not be achieved.

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COMPARATIVE ASSESSMENT OF THE ECONOMICS OF NUCLEAR POWER AND OTHER OPTIONS

G. STEVENS
Nuclear Development Division,
Nuclear Energy Agency of the OECD,
Issy-les-Moulineaux, France

Abstract

COMPARATIVE ASSESSMENT OF THE ECONOMICS OF NUCLEAR POWER AND OTHER OPTIONS.

The paper presents results on comparative costs of alternative energy sources for electricity generation, i.e. nuclear power, fossil fuels and renewable energies, drawing from recent OECD/NEA studies. Both direct costs, environmental costs and other external costs and benefits are dealt with. The alternatives considered are base load power plants capable of substantial contribution to grid connected power supply in the year 2000 or shortly thereafter. The realistic alternatives in OECD countries include advanced coal and gas fired power plants, state-of-the-art and advanced nuclear power plants and some renewable technologies which have reached the stage of commercial development. The direct costs of electricity generation are based upon the constant-money levelized lifetime cost methodology. Direct costs incorporate investments for construction and decommissioning of power plants, O&M costs and fuel cycle costs including waste management and disposal. The costs are calculated using reference performance assumptions regarding in particular lifetimes and load factors of the power plants. An assessment of the environmental costs and benefits and of other externalities is also given. The studies carried out by the OECD/NEA, in co-operation with other international organizations, highlight that the costs of electricity generation are sensitive to the discount rates adopted, the anticipated fossil fuel price trends and policies regarding environmental protection measures and regulations. At a discount rate of 5%, nuclear power would be the cheapest option in most OECD countries. At a discount rate of 10%, nuclear power is projected to retain its overall advantage over fossil fuels in France and Japan. However, at this high discount rate, the gas combined cycle would be the cheapest alternative in several countries. The paper provides detailed comparisons of electricity generation costs and their different components. The paper offers some tentative conclusions on the comparative 'full' costs of electricity generation and points out the need for further research in order to assess more comprehensively all externalities.

1. INTRODUCTION

Choices for new technologies and decisions on energy mixes for electricity generation are based upon a number of factors, including social, environmental and health impacts of the different options available. However, economic competitiveness remains a cornerstone for assessing different technologies in the process of taking decisions on future energy mixes for electricity generation.

The increasing awareness of environmental issues and the recognition of broad macroeconomic and social effects arising from technology choices have led to new approaches in cost assessment, going beyond the traditional direct cost calculations and aiming at internalizing external costs as far as feasible. Two main issues have to be addressed for implementing this approach: valuing external costs corresponding, for example, to impacts on biodiversity, social preferences and aversion to risk; and integrating external costs in the economic comparison of alternative options.

In the case of nuclear power, owing to the early recognition of liabilities arising from the generation of nuclear electricity, the classical levelized cost assessment already takes into account most of the elements related to health and environmental impacts of the full energy chain, from mining through electricity generation to decommissioning of the facilities, waste management and disposal. In particular, it should be stressed that the costs related to the application of safety standards and regulations are embedded in the investment and operation and maintenance (O&M) costs of nuclear power plants.

Moreover, while safety, radioactive waste disposal and decommissioning of facilities are explicitly covered in the direct levelized costs of nuclear generated electricity, a number of factors that are not reflected directly in cost calculations are already taken into account explicitly or implicitly by policy makers in the process of assessing the nuclear option. Therefore, when undertaking a comparative assessment of different sources for electricity generation, it is important to adopt a framework and methodology that will avoid double counting of indirect costs. Although this applies to all energy sources, it might be more significant in the case of nuclear power owing to the early recognition of potential impacts and the implementation of mitigation measures which are already reflected in the direct cost estimates of nuclear generated electricity.

2. LEVELIZED COSTS OF NUCLEAR POWER AND OTHER OPTIONS

2.1. Methodology

The adoption of a standardized methodology for cost calculations is a prerequisite for a fair comparison between different electricity generation options. The studies on projected costs of generating electricity carried out every third year by the OECD/NEA and the International Energy Agency (IEA), in co-operation with the International Atomic Energy Agency (IAEA) and the International Union of Producers and Distributors of Electrical Energy (UNIPEDE), are based upon the lifetime levelized cost calculation method [1]. This method, which discounts expenditures and incomes to their present value by applying a discount rate, reflects the time value of the money. It allows comparison of the economic merits of different candidate power plants on the basis of the ratio of total lifetime expenses to total expected outputs, in terms of equivalent present value.

The levelized cost of electricity generation per kilowatt-hour is calculated as follows:

$$EGC = \sum [(I_t + M_t + F_t)(1 + r)^{-t}] \Big/ \sum [E_t (1 + r)^{-t}]$$

where EGC is the average lifetime levelized electricity generation cost, I_t is the investment expenditures in the year t, M_t is the O&M expenditures in the year t, F_t is the fuel expenditures in the year t, E_t is the electricity generation in the year t, and r is the discount rate.

The levelized lifetime cost per kilowatt-hour of electricity generated is equivalent to the average price that would have to be paid by consumers to repay exactly the investor/operator for the capital, O&M and fuel cost expenses with a rate of return equal to the discount rate. In OECD countries, the discount rates commonly used range between 5 and 10%.

This method permits comparisons between different generation options on the basis of transparent and consistent assumptions with regard to, inter alia, lifetime and availability factors of the power plants and the rate of return.

The costs presented below, for nuclear power and other options, are calculated with this methodology and refer to base load electricity generation. The main common assumptions adopted are: commissioning of the power plants in the year 2000; 30 years economic lifetime; 75% average lifetime load factor. The costs reported include all the components of new power plant costs falling on the utility that would influence its choice of generation options. In this connection, tax on income and profit charged to the utility and any other overheads that do not influence the choice of technology are excluded. On the other hand, station specific overheads, insurance premium and R&D expenditures are included, as well as the costs of environmental protection measures, e.g. abatement technologies and emission permits. External costs that are not borne by the utility, such as health and environmental impacts of residual emissions, are not included and will be discussed in Section 3.

The costs are calculated on the basis of net power supplied to the station busbar, where electricity is fed to the grid, and expressed in constant money terms. For comparison purposes, the costs have been converted into 1 July 1991 US dollars[1] using appropriate national currency deflators and official exchange rates corresponding to that date.

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[1] In the paper, $ refers to US$ of 1 July 1991 and mills refers to US mills of 1 July 1991.

2.2. Costs of nuclear generated electricity

The latest study on projected costs of generating electricity published by the OECD in 1993 [2] focuses on plants that could be available for commissioning by the year 2000 or shortly thereafter. Information regarding nuclear power plants was provided by ten OECD/NEA countries for three reactor types: pressurized water reactors (PWR), boiling water reactors (BWR) and pressurized heavy water reactors (PHWR).

2.2.1. Investment costs

The base construction costs reported for nuclear power plants range from less than $1200/kW(e) for 1400 MW(e) PWR units (four on the same site) built in France to some $2800/kW(e) for a single 1245 MW(e) PWR unit built in the United Kingdom. Table I shows the base construction costs provided by OECD countries and the corresponding investment costs at 5% and 10% discount rates.

TABLE I. INVESTMENT COSTS OF NUCLEAR POWER PLANTS (million $)

Country	Reactor type	Base construction costs	Total levelized costs (5% discount rate)	Total levelized costs (10% discount rate)
Belgium	PWR	1746	2053	2360
Canada	PHWR	1783	2397	2830
	CANDU-3	2409	2782	3211
Finland	BWR	1509	1922	2206
France	PWR	1179	1475	1658
Germany	PWR	2400	3016	3417
Japan	LWR	2154	2483	2938
Korea,	PWR	1495	1972	2378
Republic of	PHWR	1424	1703	1879
Netherlands	SBWR	1911	2231	2459
UK	PWR	2512–2871	3010–3450	3540–4080
USA	ELWR	1237	2145	2380

Source: Ref. [3].

TABLE II. COST OF DECOMMISSIONING OF NUCLEAR POWER PLANTS

Country	Absolute value per unit (million $)	Percentage of total investment		
		Undiscounted	5% discounted	10% discounted
Belgium	270	10	1.4	0.2
Canada	203	10	0.6	~0
Finland	175	10	1.6	0.3
France	370	18	2.0	0.3
Germany	440	Not provided	2.4	0.5
Japan	267	8.7	1.4	0.2
UK	532	12–15	1.4-1.6	0.8-0.9
USA	275	13	3.7	2.1

Source: Ref. [3].

There are a number of factors which explain the broad range of construction costs reported. Some of them, such as the exchange rate and the relative costs of labour, services and goods in different countries, are due to the reference currency used. This explains largely the high costs reported by Japan for all types of power plants. Besides these factors, the major parameters having an impact on the base construction costs of nuclear power plants are the size and series effects. Significant cost reductions are obtained by building several plants at one site, which can then benefit from the common infrastructure and services, and by ordering a series of units, which reduces in particular specific R&D and design costs. It can also help by amortizing testing costs on a larger number of similar units and enhancing the productivity of qualified manpower. The relatively low construction cost of French nuclear units, for example, illustrates this point.

The typical construction times for a nuclear unit (7–8 years) are longer than those for a coal fired unit (5–6 years) or a gas fired unit (3–6 years). This has an impact on the total construction cost, especially when high discount rates are applied. At a discount rate of 10% the interest during construction represents some 25–30% of the total construction cost of a nuclear unit. Advanced reactors with simplified designs, which are under development, are expected to require shorter construction times and, therefore, to have lower construction costs.

Decommissioning cost estimates for large size nuclear power plants are based upon technical experience gained through similar tasks already carried out for decommissioning of smaller but similar research reactors [3] and for replacement of major components of large power plants. Although these cost estimates vary significantly according to national regulatory frameworks and policies regarding the timing of successive dismantling operations, they fall within a fairly narrow range when they are expressed in relative value to the total investment cost (Table II). Decommissioning costs amount to some 10–20% of the total investment cost, if not discounted. With a discount rate of 10%, decommissioning represents less than 2% of the total investment cost.

2.2.3. *O&M costs*

O&M costs represent a relatively small component of the total generation cost for nuclear power plants, although in some countries they exceed the fuel costs. They are projected to range from 5 to 16 mills/kW(e) (Table III). With a discount rate of 10%, the O&M costs represent some 15% of the total cost of nuclear electricity generation in most countries. With a discount rate of 5%, the share of O&M costs is around 20%.

TABLE III. LEVELIZED O&M COSTS OF NUCLEAR POWER PLANTS (mills/kW·h)

Country	Reactor type	O&M costs (5% discount rate)	O&M costs (10% discount rate)
Belgium	PWR	7.5	7.4
Canada	PHWR	5.3	5.4
	CANDU-3	12.3	12.2
Finland	BWR	5.4	5.4
France	PWR	10.0	9.6
Germany	PWR	12.7	13.1
Japan	LWR	10.9	11.1
Korea,	PWR	7.3	7.4
Republic of	PHWR	11.8	11.9
Netherlands	SBWR	13.8	14.0
UK	PWR	9.7–11.3	9.7–11.3
USA	ELWR	16.4	16.4

Source: Ref. [3].

The O&M costs are influenced by the technical performance of the nuclear power plants and, moreover, by safety regulations and manpower costs prevailing in different countries. Therefore, they vary significantly, both in absolute and relative value, from country to country. The reasons for the wide disparity in O&M costs in different countries have been analysed in an OECD/NEA study [4], which concluded that international cost comparisons are difficult owing to the major role of country specific factors in these costs and the lack of a harmonized methodology for calculating O&M costs.

The past trend of escalation in O&M costs has been mainly due to regulatory factors and, to a lesser extent, to the increasing cost of manpower. It may be expected that O&M costs will decrease or at least stabilize through learning from increasing experience in operating a growing number of nuclear power plants and reaching stable regulatory procedures. Moreover, advanced reactor designs have a simplified O&M process as well as enhanced performance, leading to an overall reduction of O&M costs.

2.2.4. *Nuclear fuel cycle costs*

Nuclear fuel cycle costs represent typically some 20% of the total levelized generation cost at a discount rate of 5% and less than 15% at a discount of 10% for light water reactors [3]. For heavy water reactors, the fuel cycle costs are even lower, representing some 5% of the total electricity generation costs. In recent years, these costs have decreased significantly for all types of nuclear power plants in all countries. A 40% real term reduction in estimated lifetime levelized nuclear fuel cycle costs has occurred since 1985 in OECD/NEA countries [5]. This reduction is due to improved reactor and fuel performance and lower prices of uranium and some fuel cycle services. Improved fuel and reactor performance contributed some 20% of the total nuclear fuel cycle costs. Major decreases in the prices of uranium and enrichment services, and reduction in back-end service prices contributed 80% of this reduction.

The projected nuclear fuel cycle costs [5] range from around 5 to 7 mills/kW·h for light water reactors and from 2 to 3 mills/kW·h for heavy water reactors (Table IV). The front-end of the fuel cycle includes uranium mining and milling, conversion, enrichment (for light water reactors) and fuel fabrication. The back-end of the fuel cycle includes storage, conditioning and disposal of spent fuel or reprocessing and disposal of high level waste, depending on the option adopted. In the case of the closed cycle, credits for recycled uranium and plutonium are deduced from the overall fuel cycle costs.

The most important technical factors that have an impact on nuclear fuel cycle costs are the burnup in reactors and tails assay of enrichment plants. The discount rate has little influence on the total fuel cycle costs. The levelized costs of front-end steps increase with the discount rate, while for the back-end steps, in particular spent fuel or high level waste disposal, increasing the discount rate decreases the levelized costs, since these operations occur after electricity generation.

The prices of uranium and fuel cycle services, in particular enrichment and reprocessing in the case of the closed cycle, are the main components of the nuclear fuel cycle costs. Table V shows, as an example, the share of different components in the levelized PWR fuel cycle costs for the closed cycle and the once-through cycle.

The downward trend in uranium prices that has occurred since the late 1970s has contributed significantly to the reduction of fuel cycle costs. Drastic uranium price escalation does not appear very likely in the short term owing to the existing excess inventories of fissile materials. In the long term, even if uranium prices were to rise either by market mechanisms or by an increase in the production costs, the effect on the total nuclear fuel cycle and electricity generation costs would be limited. A doubling of the uranium price would lead to only some 20% increase in the nuclear fuel cycle costs.

Technical improvements leading to efficiency gains have led to a reduction in the costs and prices of most nuclear fuel services. Enrichment prices decreased by some 30% between 1985 and 1990. This trend is expected to continue because of

TABLE IV. LEVELIZED NUCLEAR FUEL CYCLE COSTS (mills/kW·h)

Country	Reactor type	Fuel cycle costs (5% discount rate)	Fuel cycle costs (10% discount rate)
Belgium	PWR	8.3	8.5
Canada	PHWR	1.8	1.6
	CANDU-3	2.9	2.9
Finland	BWR	5.8	6.3
France	PWR	8.3	9.3
Germany	PWR	10.8	10.0
Japan	LWR	18.3	17.1
Korea,	PWR	5.3	6.0
Republic of	PHWR	3.0	3.2
Netherlands	SBWR	8.7	8.6
UK	PWR	8.1	8.1
USA	ELWR	5.2	5.5

Source: Ref. [3].

TABLE V. COMPONENTS OF THE LEVELIZED COSTS FOR THE PWR FUEL CYCLE AT 5% DISCOUNT RATE

Closed cycle		Once-through cycle	
Component	Share (%)	Component	Share (%)
Uranium	26.3	Uranium	30.0
Conversion	3.4	Conversion	3.9
Enrichment	29.7	Enrichment	33.9
Fabrication	16.0	Fabrication	18.3
Total front-end	75.4	Total front-end	86.1
Transport of spent fuel	1.8	Transport and storage of spent fuel	9.3
Reprocessing and vitrification	26.6	Encapsulation and disposal of spent fuel	4.6
Waste disposal	0.3		
Total back-end	28.7	Total back-end	13.9
Uranium credit	−2.9		
Plutonium credit	−1.2		
Total credit	−4.1		
Total	100		100

Source: Ref. [5].

efficiency improvement in the existing enrichment facilities and because of market forces as long as the supply capabilities exceed the demand. In the longer term, the enhancement of currently used technologies and the possible entry of new processes on the market should lead to cost and price reduction for enrichment services. Reprocessing costs have remained stable and might decrease through learning from experience and through efficiency gains as new industrial facilities are commissioned. The same is true for direct disposal of spent fuel.

Because of the small proportion of the total generation cost taken up by the nuclear fuel cycle component, the nuclear generation costs are relatively insensitive to fluctuations of the uranium and fuel cycle service price.

2.3. Comparison with alternative options

The technologies considered for base load electricity generation vary from country to country, according to resource availability and policy, and a number of other factors. However, fossil fuelled power plants, mainly coal and gas fired plants, are the main alternative to nuclear power in most OECD countries. In spite of the drop in oil prices in the mid-1980s, oil fired power plants are not considered as candidates for base load electricity generation in OECD countries since they remain more expensive and, moreover, raise concerns on security of supply.

The economics of renewable sources for electricity generation are highly variable and site dependent. Moreover, except for hydroelectric power plants, renewable energy power plants, which are essentially used intermittently, are often regarded as possible fuel saving plants rather than as base load contributors. The information provided by OECD countries shows that the levelized cost of electricity generated by renewable sources remains significantly higher than the cost of electricity generated by fossil fuelled or nuclear power plants. Significant cost reductions are expected in the medium and long term with technologies under development, but these are not likely to be widely available on the market before one or two decades in most countries.

The cost of fuel is the main component of the costs of fossil fuel electricity generation, with a typical share of 40-50% for coal and 70-80% for gas at a discount rate of 5%, as compared to 15-25% for nuclear power. As a consequence, the costs of fossil fuel electricity generation are more sensitive than those of nuclear electricity generation to fuel price trends and less sensitive to discount rates, which have an impact mainly on investment costs.

Over the past ten years, the costs of fossil fuel electricity generation have decreased significantly owing to lower fuel prices, which more than compensated for the increase in capital costs due to the need to meet more stringent environmental protection norms and standards. The costs of nuclear electricity generation remained more or less stable, in spite of the decrease in the fuel cycle cost. Advanced technologies under development for fossil fuels and nuclear power are expected to bring some economic gains, but a technical breakthrough that would drastically reduce electricity generation costs from nuclear or fossil fuelled power plants is not likely to occur in the short term.

The last OECD study on projected costs of electricity generation [4] has shown that, at a discount rate of 5%, nuclear power will be cheaper than coal fired power in most countries which provided data for both, the exceptions being the UK, where the nuclear cost data were based upon a first of the kind unit (Sizewell B), and the western part of the USA, where the coal price is very low. At the same discount rate, nuclear power is also cheaper than gas in all countries except the UK.

At a discount rate of 10%, nuclear power loses much of its competitive advantage in comparison with electricity generation by both coal and gas. However,

TABLE VI. GENERATION COST RATIOS (million $)

Country	Nuclear/coal		Nuclear/gas	
	5%	10%	5%	10%
Belgium	0.91	1.09	0.88	1.14
Canada	0.88	1.15	0.57	0.88
Finland	0.86	1.06	0.85	1.16
France	0.65	0.77	0.60	0.78
Germany (domestic coal)	0.66	0.83	—	—
(imported coal)	0.79	0.97	—	—
Japan	0.85	0.94	0.69	0.92
Korea, (PWR)	0.75	1.00	—	—
Republic of (PHWR)	0.74	0.88	—	—
Netherlands	1.04	1.14	—	—
UK	1.02	1.27	1.11	1.69
USA	0.96	0.99	0.90	1.19

Source: Ref. [3].

nuclear electricity generation remains cheaper than or equal to coal electricity generation in seven OECD countries and cheaper than electricity generation by gas in three countries. This sensitivity to discount rates arises directly from the large share of the capital component in the case of nuclear power.

The competitiveness of gas for base-load generation is a new trend, resulting from the development of more efficient technologies, in particular the use of combined cycle power plants with low investment costs. However, the cost of gas generated electricity is very sensitive to the price of gas and, therefore, an increase in gas prices that might occur as the demand grows would reduce the competitive margin of gas fired power plants.

The ratio of the projected costs of nuclear, coal and gas generated electricity, in a given country, is typically between 0.6 and 1.4 (Table VI). The uncertainties on future fuel prices, technical performance improvements and a number of other factors generally lead countries and utilities to include in their systems a mix of different sources, taking into account economics, security of supply and other national or global concerns and objectives such as environmental protection.

3. BEYOND DIRECT COSTS

Direct cost comparisons are a key element in comparative assessment of different electricity generation sources. However, as long as the full costs to society of any given option are not entirely reflected in the direct costs as described above, there is a need to take into account other parameters and factors in order to comprehensively assess and compare alternative options.

The costs and benefits to society that are generally not incorporated in the direct costs of electricity generation include: macroeconomic impacts, such as job creation and price stability; strategic factors, such as security of supply and energy resource management; and externalities that are not borne directly by consumers but by society at large, such as health and environmental impacts of residual emissions.

The increasing awareness of global impacts, in particular on the environment, and the recognition of the concept of sustainability are leading analysts and decision makers to aim at incorporating these parameters explicitly or implicitly in the comparative assessment process.

A number of international studies carried out recently provide some results which allow broad economic impacts [6] and externalities [7] of different electricity generation sources to be assessed. However, the uncertainties prevailing on many aspects prevent final conclusions on these issues to be drawn. While the ExterneE project [7] resulted in the development of a methodology for transparent and comprehensive evaluation of impacts from electricity generation systems, it did not provide an assessment of the total overall impact of any of the fuel cycles analysed. The OECD/NEA study on broad economic impacts of nuclear power [6] concluded that, for nuclear power, most but not all of the relevant costs were captured within the classical levelized cost estimations. This study also concluded that "future attention should focus on the external costs of fossil fuel combustion".

The following sections address briefly the issue of external costs, with emphasis on health and environmental aspects in the light of their major relevance in connection with sustainability and of their influence on policy making in the power sector.

3.1. Health and environmental issues

Most health and environmental impacts of electricity systems are already reflected in the direct costs of electricity and, therefore, in the prices paid by the consumers. The adoption of emission standards and environmental protection regulations have led to the implementation of control technologies and/or taxes or permits which have a direct impact on costs borne by the utilities. Risks of accidents are also partly reflected in costs through insurance premiums. However, residual emissions and risks entail additional costs for society which should be evaluated for estimating the full cost of different electricity generation options.

3.1.1. Residual emissions and wastes from normal operation

Atmospheric emissions from fossil fired power plants include sulphur dioxide, nitrogen oxides, carbon dioxide and particulates. The use of fossil fuels for electricity generation is also responsible for emissions arising from extraction, processing and transport of coal, gas or oil. Increasing concern about the environment has led to more stringent standards and regulations and the implementation of cleaner technologies and/or abatement devices, reducing these emissions, at least in most OECD countries, to a level thought to be harmless to health or the environment. Therefore, the residual atmospheric emissions from fossil fuel based electricity generation systems do not impose significant external cost on society, with the possible exception of the global climate change induced by carbon dioxide emissions. In this regard, efficiency improvements resulting in lower fuel consumption per unit of electricity generated have contributed to reducing the potential impact of fossil fuel chains. However, there is a residual risk which, at present, cannot be evaluated with a reasonable level of certainty, taking into account the status of scientific knowledge of climate mechanisms and of the specific impacts of global climate change in different regions of the world.

Taking into account all fuel cycle activities, nuclear power produces negligible quantities of non-radioactive atmospheric emissions. Standards and limits for radioactive emissions were developed several decades ago and the general principles currently applied in most countries are those set by the International Commission on Radiological Protection (ICRP) in 1977, revised subsequently according to the progress in scientific knowledge [8]. The ICRP stated that it "believes that the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk" [8]. Therefore, radiation protection limits that are set up to protect humans, more than satisfy the requirements for the protection of other living creatures, health and the environment. The potential health impact of radioactive emissions from nuclear power plants and fuel cycle facilities can be evaluated by the doses from releases, which are assessed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). According to UNSCEAR, measured or calculated exposures of workers and the public to routine radioactive emissions from nuclear power activities amount to less than 0.1% of the public's exposure to natural radiation arising from minerals, atmospheric radon and cosmic rays [9]. This means that no measurable external cost is associated with these emissions.

Electricity systems based on renewable energy sources such as nuclear power are practically free from airborne emissions. Photovoltaic solar systems might generate carbon dioxide emissions indirectly when fossil energy is used in the process of fabricating solar cells (this applies also to nuclear power when fossil energy is used for uranium enrichment). Biomass might generate carbon dioxide when the energy system is not set up to be sustainable, i.e. compensating carbon dioxide emissions from burning biomass by its capture from growing biomass fuel. Some hydropower projects lead to methane (a greenhouse gas) emissions arising from the decomposition of biomass in flooded reservoirs. However, these residual emissions are generally estimated in most cases to generate negligible additional costs to society.

Wastes arising from electricity generation are a concern mainly for coal fired and nuclear power systems. The costs associated with the management and disposal of these wastes are essentially captured by the levelized cost estimations. However, in the case of coal fired power plants, the volumes of waste are very large, some 300 000 tonnes per year per GW(e), and, although they contain hazardous heavy metals, these wastes are disposed of at ground level and are not isolated from the biosphere.

On the other hand, the total volumes of radioactive wastes arising from nuclear electricity generation are rather small. More than 99% of the total radioactivity of these wastes is contained in high level waste (HLW) and the remaining part in low and intermediate level waste (LLW and ILW). Per GW(e) installed, conditioned HLW represents a few tens of cubic metres per year, and LLW and ILW represent some 500 cubic metres [10]. There is wide scientific and technical consensus that safe disposal of all types of radioactive waste, including HLW, ensuring their long term exclusion from the biosphere, is feasible [11]. The costs of radioactive waste management and disposal have been estimated on the basis of laboratory testing experience and engineering studies [12] and, as indicated in Section 2, they are included in the direct levelized cost estimates provided for nuclear electricity generation. The radiation protection criteria applied for the implementation of radioactive waste repositories imply that residual radioactive emissions will remain as low as possible and in any case lower than the level at which there will be significant health risk for present and future generations. Therefore, external costs associated with health and environmental effects arising from radioactive waste disposal are estimated to be negligible.

3.1.2. Abnormal operation and accident risks

The potential risks of severe accidents, i.e. accidents with significant off-site risk to people and the environment, are recognized for all energy systems but are not very well documented. The available data on severe accidents and their consequences are by no means complete or comprehensive. With the exception of nuclear power, data on the frequency of and the health and environmental damages caused by severe accidents are not systematically collected by a single national or international organization. There are virtually no data on delayed effects on health from severe accidents arising in electricity generation chains, and their ultimate long term effects on the environment are difficult to establish owing to their rare occurrence. It should be pointed out that collection of data and information on severe accidents and their consequences is based on two different approaches: consideration of actual historical occurrence for most electricity generation systems and probabilistic forecasts of likely occurrence mainly for nuclear power. Therefore, their comparative assessment within an integrated framework might be somewhat misleading.

Rough estimates, based upon available data, suggest that human health risks from severe accidents from nuclear, oil and gas chains are of the same order of magnitude as, and two orders of magnitude smaller than, those from the hydropower option. However, any direct comparison in this regard should be interpreted with great care owing to the lack of a comprehensive harmonized database [13], as mentioned above.

Since accident risks are partly incorporated in the direct costs borne by producers through insurance and wages that reflect the risk of exposed staff, it is difficult to assess the residual external costs arising from low probability/high consequence accidents. The summary report on the ExternE study [7] states that: "At this time there has been no general consensus on a methodology to assess the external cost of severe accident". Furthermore, aversion to risk often entails, especially in OECD countries, individual willingness to pay more in order to avoid accidents than would be calculated by the risk based cost approach.

A review of studies on financial risks associated with severe accidents in the power sector shows that there is a wide range of estimates because of the prevailing uncertainties and, moreover, the assumptions adopted in different countries with regard to the monetary value of health, particularly in connection with fatalities, and environmental damages resulting from accidents. In the case of nuclear power, cost estimates for the consequences of the most severe accident which occurred — Chernobyl — ranged from US $ 8000 million to US $ 200 000 million. However, most of the estimates provided indicate that the external cost associated with risks of severe accidents remains in any case lower than 1 % of the direct cost of electricity generation and generally lower than 0.1%.

3.1.3. Other environmental impacts

Other environmental impacts, with the exception of land requirements, which are already covered by the direct costs of electricity generation, are of a more qualitative nature and are difficult to express in term of costs. Visual intrusion and reduction of biodiversity, for example, cannot be easily measured by physical numerical indicators; their monetary valuation, which is essentially context dependent, remains highly subjective. In most cases, the value of these impacts is estimated by the willingness of people to pay for avoiding or reducing them. As an example, the lower prices of properties in areas exposed to noise or areas where the initial environment has been (or might be) degraded reflect the economic impact/external cost of the activities creating environmental impacts.

These impacts should be evaluated on an 'ad hoc' basis for each specific project, taking into account local conditions, since they cannot be fully assessed by generic methodologies and within generic frameworks. However, published studies and analyses carried out so far seem to indicate that their economic effect on the total cost of electricity generation is not significant.

3.2. Other externalities

Broader impacts of technology choices in the power sector that entail external costs or benefits include: secondary investment effects; stability of electricity costs and prices; balance of payments equilibrium; regional and national technological, industrial and socio-cultural development; security of supply; and natural resource management.

Most of these effects are interrelated and can be quantified only, if at all, in a country specific context. Macroeconomic models developed recently have improved significantly the capabilities for dealing with these various parameters in an integrated framework. However, there is no single model that would allow all these aspects to be tackled and that would provide an estimate of their integrated overall economic impact within the time frame implied by the long term effects of choices and policies in the power sector.

With regard to nuclear power, in an analysis carried out by the OECD/NEA in 1992 [6] it was estimated that the non-environmental externalities fall within the range of uncertainty surrounding the standard projected levelized cost of electricity generation and it was concluded that they do not yield costs or benefits that will significantly influence the competitiveness of nuclear power with alternative power generation.

4. CONCLUDING REMARKS

In OECD countries, the direct projected costs for base load electricity generation are fairly close for nuclear power plants, coal fired plants and combined cycle gas fired plants. Renewable sources are generally not considered for base load electricity generation and, in most cases, would not be competitive.

For advanced nuclear power plants under development, it is expected that significant investment cost reductions will result from smaller volumes for the same capacity, simplified design and shorter construction times. For example, the projected investment cost for the AP600 is 25% lower than that for the 600 MW(e) reactors of current design. Advanced coal and gas fired power plants are also expected to bring cost reduction through technological improvements and enhanced efficiency. However, while coal, gas and nuclear technologies for electricity generation seem to have potential for continuous marginal cost reductions, none of them is expected to bring any breakthrough that would lead to a drastic cost decrease.

Economic choices would, therefore, differ from country to country, depending mainly on the prevailing discount rates and on the expected prices of fossil fuels. In this context, policy issues, such as security of supply, and social and environmental concerns, such as public acceptance and the potential risks of global climate change, are likely to play an important role in the decision making process for the electricity sector.

For all countries that do not enjoy large resources of domestic fossil fuels, nuclear power has significant advantages in terms of security of supply because strategic nuclear fuel inventories can be established at relatively low economic penalty.

Social acceptability of nuclear power remains a concern in most OECD countries. The emergence of an international consensus on safety (adoption of an international convention on the safety of nuclear power plants in 1994) and radioactive waste disposal (publication of a report on the collective opinion on the environmental and ethical basis of geological disposal of radioactive waste in 1995 [14]) is expected to enhance public acceptance of nuclear power. Increasing worldwide experience of reliable and safe operation of a large number of nuclear units will also contribute to demonstrating the actual technical, economic and safety performance of nuclear power and, therefore, to reinforcing its public acceptance.

Without significant reliance on nuclear energy, it is indeed difficult to envisage how the increasing demand for electricity can be met economically and without detriment to the environment.

Taking into account the existing scientific know-how, technical experience and industrial capabilities existing in OECD countries and the amount of fissile material resources available, nuclear power could significantly increase its share of electricity generation in the medium and long term, contributing to the implementation of sustainable energy mixes in a number of countries.

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SOME ASPECTS OF THE DESTRUCTIVE IMPACT OF FOSSIL FUEL COMBUSTION AND MINING ON THE ENVIRONMENT

J. PALIGE, A.G. CHMIELEWSKI
Institute of Nuclear Chemistry and Technology,
Warsaw, Poland

Abstract

SOME ASPECTS OF THE DESTRUCTIVE IMPACT OF FOSSIL FUEL COMBUSTION AND MINING ON THE ENVIRONMENT.

In Poland, over 80% of the power is generated by combustion of coal and lignite. In the process of coal fired power generation, SO_2, NO_x, heavy elements and trace elements are emitted into the air, and the water is contaminated by saline water discharged from mines. During combustion, significant quantities of natural radioactive elements are mobilized and emitted into the environment together with gases, ash and water. The total amount of water pumped daily from all coal mines in Poland is about 920 000 m^3. The quantity of salts contained in this water is about 9000 t. The concentration of ^{226}Ra in highly mineralized water may be as high as 390 kBq/m^3. Water purification leads to the formation of radioactive deposits with an activity of about 400 kBq/kg. The presence and concentration of ^{222}Rn gas in mines is measured and controlled using portable radiometers. Using the RFX method and spectrum analysis, the concentrations of 15 elements in products of coal and lignite combustion were determined. Large emissions of radioactive elements were found. Combustion of coal in power stations of 1000 MW(e) causes emissions of 138×10^3 t SO_2 and 20.9×10^3 t NO_x per year. New technologies for removal of gas pollutants were developed. A pilot plant based on the electron beam technology for simultaneous SO_2 and NO_x removal was constructed and tested. Over the last years, many nuclear devices for quality control of coal and lignite have been developed. Devices have been constructed for measuring the ash contents, dust concentration, and sulphur and moisture contents of fossil fuel both for laboratory and industrial applications. The opponents of nuclear power generation in Poland argue that a nuclear power plant emits significant quantities of radioactive gases to the atmosphere and produces liquid and solid radioactive wastes. The practice in other countries has shown that the daily releases to the atmosphere of one WWER-440 type power reactor are about 2.1×10^{11} Bq noble gases, 2.4×10^6 Bq ^{131}I, 4×10^5 Bq ^{137}Cs and 7.8×10^3 Bq ^{89}Sr, and that about 30 m^3 liquid low level radioactive wastes per day are generated. It is pointed out that power production based on coal combustion generates amounts of radioactive materials comparable with those of nuclear power plants and, in addition, large quantities of gases (SO_2, NO_x, CO_2), dust and ash.

1. INTRODUCTION

In Poland, the programme of nuclear power development was stopped in 1990 because of the insufficient information of the population regarding nuclear energy and its impact on the environment. It was argued that nuclear power is not safe (Chernobyl effect) and that it causes contamination of the environment by emission of radioactive substances (gases, wastes, etc.). As a result, over 80% of the power is generated by combustion of fossil fuels, particularly coal and lignite. Recently, intensive studies have been performed regarding monitoring and control of the destructive impact of the traditional energy generation processes on the environment. New technologies and techniques for decreasing emissions of contaminants to the environment have been elaborated and applied. Nuclear techniques have also been widely applied in these studies, particularly for monitoring and control.

As a result of these studies, nuclear power is now regarded in Poland as a more safe and beneficial source of energy from the point of view of environmental protection.

The paper discusses the main impacts on the environment connected with mining and combustion of fossil fuels:

- Emission of dust containing heavy and trace metals and natural radioactive isotopes;
- Inflow of mine waters containing natural radium isotopes;
- Inflow and discharge of saline waters;
- Emission of SO_2 and NO_x in flue-gases to the atmosphere.

Nuclear techniques applied to the control and reduction of pollutant emissions are also presented. On the basis of literature data, the nuclear and the traditional (coal combustion) processes of energy production are compared regarding their impact on the environment.

2. ENVIRONMENTAL IMPACT OF COAL MINING

During coal mining, a significant quantity of contaminated water is produced through inflow of underground water and from washing of the coal. This waste water contains large quantities of dissolved salts and in some cases natural radioactive isotopes.

2.1. Impact of saline waters

River water salinity caused by coal mines is a specific problem in Poland. The amount of salts contained in mine water discharged daily into the rivers is about 9000 t [1]. The elevated salinity hampers self-purification of rivers and causes destruction of water plants and corrosion of municipal and industrial water supply systems. The total amount of water pumped daily from all coal mines in Poland is about 920 000 m^3. The salinity of waters from different coal mines varies greatly. The salt concentration in some mine waters exceeds 70 g/L.

During the last years, intensive investigations have been performed in Poland to solve the problem of excess salinity of river waters. Protection against salinity involves purification of mine waters in special installations for water desalination where evaporation or membrane processes (reverse osmosis) are applied. The first installation of this type is in operation and treats 14 000 m^3/d of salty drainage water from mines [2]. Nevertheless, so far, the majority of contaminated mine waters is discharged into natural water reservoirs without cleaning.

2.2. Impact of mine waters with radium isotopes

Waters from coal mines with high mineralization often contain natural radioactive isotopes. Elevated concentrations of ^{226}Ra, ^{228}Ra and ^{224}Ra have been found. The concentration of ^{226}Ra in water may be as high as 390 kBq/m^3 [3]. The amount of waters released from mines is very large; it varies from about 1 m^3/h to 30 m^3/h for different mines. Sometimes, radium bearing waters also contain barium ions. In this case, radium is coprecipitated with sulphates, whereby deposits are formed in which the concentration of ^{226}Ra may be as high as 400 kBq/kg. Radioactive deposits may cause pollution of the natural environment. Radium bearing waters without barium ions do not form deposits. In this case, radium is transported with the water to rivers, where dilution takes place.

In recent years, purification of water containing radium has been performed. In the case of underground storage of radioactive solid wastes produced in coal mines, methods based on precipitation and sedimentation of radioactive deposits are applied.

2.3. Impact of ^{222}Rn

The presence of the natural radioactive gas ^{222}Rn and its short lived decay products in the air of underground mines may pose a serious hazard for mine-workers. This radiation hazard is checked with various methods, using different measuring instruments. Over the past decade, there have been significant developments in the techniques and methods of monitoring radon and radon daughters. At the Institute of Nuclear Chemistry and Technology (INCT) in Warsaw, a portable mining radiometer was constructed; this was approved by the Higher Mining Office for application in coal mines where methane is expected to be present [4]. A new version of this radiometer not only provides full control of the measuring process but also allows the measuring results to be stored in the computer memory. The instruments can be used for examination of the radiation hazard to miners and for checking the mine ventilation systems.

3. ENVIRONMENTAL IMPACT OF COAL COMBUSTION

The destructive environmental impact of coal mining is known, but the hazards connected with coal and lignite combustion are no less serious. During combustion,

TABLE I. AVERAGE CONTENTS OF TRACE ELEMENTS AND ASH IN COAL AND SPECIFIC ACTIVITY OF ^{40}K, ^{226}Ra AND ^{232}Th

Element or isotope	Average	Range	World average (Ref. [6])
S (%)	0.53	0.18–0.85	2.0
K (%)	0.24	0.01–0.58	0.01
Ca (%)	0.35	0.08–0.78	1.0
Ti (%)	0.13	0.03–0.81	0.05
Cr (ppm)	28	5–63	10
Mn (ppm)	121	20–660	50
Fe (%)	0.77	0.25–2.1	1.0
Ni (ppm)	44	<6–94	15
Cu (ppm)	26	13–50	15
Zn (ppm)	38	13–156	50
Br (ppm)	41	9–105	—
Rb (ppm)	27	<6–56	100
Sr (ppm)	198	68–495	500
Zr (ppm)	48	<7–130	—
Pb (ppm)	27	<8–61	25
Th (ppm)	5.1	<1.2–12	—
U (ppm)	2.7	0.9–5.1	1.0
K-40 (Bq/kg)	131	2–317	—
Ra-226 (Bq/kg)	34	10–64	—
Th-232 (Bq/kg)	20	4–48	—
Ash (%)	20.9	5.4–35.7	—

TABLE II. AVERAGE CONTENTS OF TRACE ELEMENTS IN ASH AND SPECIFIC ACTIVITY OF ^{40}K, ^{226}Ra AND ^{232}Th

Element or isotope	Average	Range
S (%)	1.31	0.16–4.87
K (%)	1.69	0.52–2.51
Ca (%)	2.96	0.58–10.3
Ti (%)	0.70	0.39–1.15
Cr (ppm)	253	65–831
Mn (ppm)	777	71-3054
Fe (%)	4.96	1.25-16.7
Ni (ppm)	264	88–620
Cu (ppm)	109	40–259
Zn (ppm)	240	54–2073
Br (ppm)	17	5-103
Rb (ppm)	132	21-214
Sr (ppm)	760	126–3422
Zr (ppm)	187	119-381
Pb (ppm)	145	10-900
Th (ppm)	22.5	12.8–44.2
U (ppm)	11.4	6.5–20
K-40 (Bq/kg)	640	203–999
Ra-226 (Bq/kg)	141	81–248
Th-232 (Bq/kg)	102	52–179

significant quantities of dust, ash and flue-gas are produced. These combustion products cause large environmental pollution connected with the emission of heavy, trace and radioactive elements in the ash and of SO_2 and NO_x in the gases.

3.1. Emission of trace and natural radioactive elements with ash

Power generation leads to substantial emissions of some elements. It is important to assess the emissions of each trace element from coal combustion and the potential effects of these trace elements on the environment. For correct assessment of emissions, techniques and apparatus are required for detection and analysis of trace elements in coal and in combustion products.

At the INCT, investigations were carried out to determine the contents of trace elements in 150 samples of pre-combustion coal or lignite and of ash from different regions of Poland [5]. The XRF method was applied for measuring the contents of 15 elements (S, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, Br, Rb, Sr, Zr, Pb) in these samples. A spectrum analysis was carried out with the AXIL–QXAS programs elaborated by the IAEA. The natural activity of samples and the contents of radioactive isotopes were determined by gamma spectroscopy, applying the computer program GANAAS elaborated by the IAEA. Table I presents data from coal measurements and compares them with the world average values [6].

Corresponding data from ash measurements are presented in Table II. Such measurements are being carried out continuously. The principal aims of this kind of measurement are the formulation of the complex criterion of the environmental impact of coal and ash and the calculation of emission factors for different metals.

3.2. SO_2 and NO_x emissions

In the process of coal combustion for power generation, a 1000 MW power station causes annual emissions of 138×10^3 t SO_2 and 20.9×10^3 t NO_x [7]. Power generation and heat production for both the industrial sector and the municipal sector cause 90% of the SO_2 emissions and about 60–70% of the dust and NO_x emissions in Poland. Conventional air pollution control technologies (wet line scrubbing and selective catalytic reduction have been developed to a high level and no significant cost reduction can be expected in the near future. Thus, it is necessary to develop second generation technologies. The electron beam technology is one such method. It is a dry process permitting simultaneous removal of SO_2 and NO_x from flue-gases; the final product can be used as a fertilizer [8]. A pilot plant with a flue-gas flow capacity of up to 20 000 Nm^3/h was constructed. Two accelerators were installed in series on a reaction vessel. The beam power of each unit is 50 kW and the electron energy is 500–700 keV. The removal efficiencies obtained are about 95% for SO_2 and about 80–85% for NO_x.

4. NUCLEAR INSTRUMENTATION FOR QUALITY CONTROL OF COAL AND LIGNITE

During the last years, many nuclear instruments have been developed in Poland for quality control of both laboratory and industrial coal and lignite. At the INCT, instruments for determination of ash in lignite [9] and a dust concentration monitor [10] have been developed. A computer controlled laboratory instrument for determination of ash and of calcium and iron oxides in lignite is based on XRF and on scattering of low energy X rays from a ^{238}Pu source. For combustion control in connection with prediction of the ash fusion temperature in the coal industry it is very important to know the contents of ash, iron and calcium. The new, improved version of the airborne dust concentration monitor is based on the measurement of beta particles absorbed by the dust mass deposited on the air filter; a ^{147}Pm source is used. The measurement precision of the dust concentration is 1–1.5% for a dust mass of 1 mg.

The Polish Centre for Electrification and Automatization of the Mine Industry EMAG is a large producer of nuclear instruments for both laboratory and industrial applications [11]. For laboratory purposes, a radiometer for sulphur content measurement (based on the Mössbauer effect), a radiometer for ash and sulphur content measurement and a radiometer for measuring the ash and humidity content in coal have been developed. All these devices are used in mine laboratories for control of the coal quality.

Another group of devices for on-line measurements includes: a continuous ash radiometer (based on backscattering of radiation from a ^{241}Am source) installed on belt conveyors; the system ALFA-04 for continuous measurement of the ash content and humidity of coal on conveyors; and the ash radiometer GAMMA-2E (based on gamma radiation absorption from ^{241}Am and ^{137}Cs sources) for continuous quality monitoring of lignite in mines and power stations. The measurement data include the directly measured values of the ash content, the calculated moisture contents and the calculated heating values. The readings are transmitted to a central dispatch room for further evaluation.

5. COMPARISON OF NUCLEAR AND COAL COMBUSTION METHODS OF ENERGY PRODUCTION

As mentioned above, the programme of nuclear power generation in Poland was stopped in 1990. Several years later, the new national energy programme was adopted according to which a considerable amount of electricity is to be generated by nuclear power plants in the first decade of the next century. The changed attitude towards nuclear power in Poland is connected with the energy balance of the country, the more precise evaluation of coal and lignite deposits, and a new fundamental assessment of the impacts of nuclear and conventional energy production processes on the environment.

For coal mining the average quantity of pollutants produced per 1 t of coal are: total water (with natural radioactive elements) — 2.68 m^3/t, saline water — 0.86 m^3/t and NaCl — 25.2 kg/t. For combustion of coal with 3.5% S content in power stations of 1000 MW(e) the quantities of pollutants produced per year are: 138×10^3 t SO_2, 20.9×10^3 t NO_x, 21 t CO, 210 t aromatic hydrocarbons, 4.5×10^3 t dust and about 9–10% ash (with natural radioactive elements).

The opponents of nuclear power generation in Poland argue that a nuclear power plant emits significant quantities of radioactive gases to the atmosphere and produces liquid and solid radioactive wastes. The practice in other countries has shown that the daily releases to the atmosphere of one WWER-440 type reactor are about 2.1×10^{11} Bq noble gases, 2.4×10^6 Bq ^{131}I, 4×10^5 Bq ^{137}Cs and 7.8×10^3 Bq ^{89}Sr, and that about 30 m^3 liquid low level radioactive wastes per day are generated.

It should be pointed out that power production based on coal combustion generates amounts of radioactive materials (solid mine deposits, saline waters with Ra isotopes, ashes with natural radioactive elements) comparable with those of nuclear power plants and, in addition, large quantities of gases (SO_2, NO_x, CO_2), dust and ash.

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TOWARDS SUSTAINABLE ELECTRICITY POLICIES
Challenges for International Co-operation

(Summary of Round Table)

Chairman

R. SHELTON
United States of America

SUMMARY OF ROUND TABLE

Towards Sustainable Electricity Policies
Challenges for International Co-operation

Rapporteurs: **M. Munasinghe** (Sri Lanka)
R. Pachauri (India)
C. Cordoba Salazar (Colombia)
N. Sudja (Indonesia)
K. Yeager (United States of America)
D. Zhou (China)

Panelists: **G. Mackenzie** (United Nations Environment Programme, UNEP)
C. Gurcok (United Nations Industrial Development Organization, UNIDO)
G. Stevens (Nuclear Energy Agency of the OECD, OECD/NEA)
P. Valette (European Commission, EC)
P. Zaleski (France)

INCORPORATION OF ENVIRONMENTAL AND HEALTH EFFECTS

A large number of integrated assessment frameworks have been or are being developed. In the past, integrated assessment was considered as a simple process, the application of which could help to achieve zero risk or zero emission. More recently, however, integrated assessment was found to be more complicated and therefore the assessment frameworks which included economic factors have been developed to include social factors and, most recently, environmental factors in an integrated form. Work on framework models is in progress.

Although progress in the assessment of health and environmental impacts has been made, there are still uncertainties and unresolved issues. In order to comprehensively assess health and environmental impacts of energy systems, further investigations are needed.

Data for health and environmental risk analysis are particularly deficient and emphasis should be placed on improvement of these data. We still do not know enough about the risks of various environmental or health impacts or we have not identified all potential pathways and impacts. Environmental risk in connection with health risks due to poverty is an important issue in developing countries. For these countries, alleviation of poverty is an issue of first priority, whereas environmental risks may be regarded as having second or third priority.

Therefore, an international consensus on the assessment framework has to be reached. At present, such a consensus does not exist because of, for instance, the complexity of environmental impacts and the difficulty of quantifying some of the components, such as health risks and the values placed on human health damages (this is illustrated by the difficulties in evaluating health impacts in industrialized and developing countries, mentioned in the current Second Assessment Report of the Intergovernmental Panel on Climate Change).

There is a significant lack of results on health effects of electricity production, distribution and use. Subjects such as health risks to people living near electric power substations and high-tension lines would require particular attention. This problem is of public concern in industrialized countries and some countries are conducting scientific studies to determine the seriousness of the risks. Several conferences have been devoted to these issues, but scientific information is still lacking. However, this topic remains an important public problem and more scientific studies are needed.

INCORPORATION OF SOCIAL FACTORS

The valuation of cost should not be limited to physical factors only but should also include mental and social factors; however, these are seldom incorporated in analyses. The DECADES project, in the present phase, is not a public information oriented kind of project. However, it is certainly possible to address social issues by using the results of certain studies; some of these studies have been carried out within the DECADES project and other studies can be carried out by using the DECADES tools and other tools. Within the DECADES project, it is possible to calculate the various kinds of emissions, environmental burdens and waste quantities. These calculations may not provide direct information on social effects, but they are at least a starting point for such evaluations. Obviously, the economic issue — which is a kind of social issue — is already rather fully incorporated in the analyses.

Analyses should incorporate the future evolution of technologies but should also consider the future evolution of social structures. This includes not only the growth of the population, which will require more energy, but also the development of megalopolises. There is an interaction between energy policy and urban development policy, and in future there may be an even greater move towards urbanization. This may actually affect the kind of technology that should be implemented; for example, decentralized power systems based on diffuse energy sources are not well adapted to meet the energy demands in large cities. On the other hand, highly centralized power systems can be used much better if more people live in large cities (regardless of whether this is desirable or not from social or other viewpoints). In any case, this is an issue that needs to be addressed.

ADDRESSING GLOBAL AND LONG TERM ISSUES

A key question is whether global and long term effects can be addressed comprehensively and whether all possible pathways leading to these two categories of effects can be dealt with.

Attention should be given to global issues, mainly greenhouse gas emissions and climate change. There are different kinds of environmental concerns in different countries, according to the social and economic conditions. However, many uncertainties regarding global warming or waste disposal still exist, and more work has to be done regarding the relationship between future power generation development and these issues.

There is no consensus on whether global environmental issues should be decoupled from regional and local issues. It seems that local effects and global effects or impacts are inherently decoupled from each other, since local effects are linked to the decision of a given regulatory body, whereas global effects are major issues that might not be influenced greatly by unilateral action by a State or even a group of States.

On the other hand, linking global and local issues is considered to lead to 'win–win' situations. By addressing global warming and reducing carbon emissions it will be possible to solve problems in connection with local environmental effects, which are of immediate priority for most developing countries.

PROGRESS MADE IN THE DEVELOPMENT OF TOOLS AND FUTURE WORK

Progress has been made in building up better databases and analytical capabilities. An extremely broad range of models and a large number of data are now available. Results of studies in which these have been used were presented at the Symposium. However, it is difficult to know whether data sets are compatible and therefore it will be necessary to check and ensure the compatibility of different data sets. Only when this work is done will it be possible to consider an approach towards establishing an internationally validated and recognized set of databases and analytical tools. Although it will never be possible to say that a certain approach is the only one to be used, it might be helpful to have a number of well elaborated and generally accepted approaches. A problem continuously encountered by analysts is that one group finds one result and another group finds a different result, and the two groups cannot figure out why they have different results. Therefore, agreement should be reached on methodologies, a general framework, the data used and the way in which they are presented. If an international group of reviewers could reach an agreement on these matters, an enormous amount of time could be saved, since it would be possible to develop a structure that would allow more consistent and compatible comparisons to be made without having to argue about inconsistencies in the different basic data and approaches.

It is also recommended to use assessment results for providing valuable feedback in order to guide further development and refinement of scientific and technical data and information, and for improving the assessment frameworks. There is a need to develop analytical frameworks that can provide good approximations to the optimal solutions without the collection of all data. This would be a promising objective for follow-up work, but it may still be unrealistic.

The problem is that the information is not only very site specific but also extremely culture specific. The only thing that can be done is to establish, as factually as possible, a sort of biophysical economic database, some analytical methods and a framework for comparison, but it has to be left to the practitioner to find out how these tools can be utilized in a particular country or region.

Many models are now available for data and analysis, which shows the enormous progress made since the Helsinki Symposium in 1991. The next step would be to use these tools in order to increase the experience and to ascertain the merits and weaknesses of the different models. In this area, the role of intergovernmental bodies is to monitor the progress of work, to exchange experience and to help develop more effective models and applications.

There is confusion about the actual capabilities of analytical models. When they are presented, the impression is sometimes given that the models are able to treat everything and to answer all questions. It would be more effective if discussions of modelling applications would concentrate on the most important and specific issues.

In developing countries, large investments are projected to be required for the power sector. From the case studies it appears that there are still large uncertainties in the estimates of investment costs for different electricity supply options. Therefore, it is recommended that more work be done in order to reduce these uncertainties and to provide better guidance to decision makers.

DIFFERENCE IN THE ISSUES TO BE ADDRESSED BY INDUSTRIALIZED AND DEVELOPING COUNTRIES

More than 2000 million people in the world do not have access to electricity. Industrialized countries have the necessary means of reducing the health and environmental impacts of electricity generation, whereas for developing countries the most important issue is to implement additional electricity generation capacities to meet their requirements.

The growth rate of electricity demand is more or less stagnating in industrialized countries and is only about 1 or 2% per year. In many large developing countries, such as China and India, the growth rate of electricity demand is as high as 8 or 9%. Industrialized and developing countries have a very different appreciation of environmental concerns. Because of their high levels of per capita energy consumption, industrialized countries regard global environmental issues as being very significant. This is, however, not the case in most developing countries, which are faced with more immediate local environmental issues such as emission of particulates, or regional issues such as acid rain and sulphur deposition. As a result, there are many differences in the priorities assigned to the issues that have to be addressed. For example, industrialized countries may pay high attention to amenity values (e.g. loss of visibility, visual intrusion on landscape, noise levels) associated with certain energy systems, whereas developing countries are likely to place high priority on expanding energy supplies as a means of promoting economic growth and may assign lower priority to environmental issues. Therefore, it is necessary to accelerate the transfer of renewable and clean technologies that can be used to meet both the required energy demands and the environmental protection goals.

CO-OPERATION BETWEEN INDUSTRIALIZED AND DEVELOPING COUNTRIES

Industrialized and developing countries have common objectives, namely satisfying the requirements of both energy supply and environmental protection. These can be achieved by strengthening and broadening co-operation between the countries. For the implementation of mitigation measures, international co-operation is required, as well as technical and financial assistance of developing countries by industrialized countries. Industrialized countries have better access to clean and advanced technologies, and more financial capabilities and tools that can be used for comparative assessment (these tools are usually given to developing countries free of charge). It is necessary to assist developing countries in implementing clean technologies in order to minimize adverse impacts from the power sector while satisfying the energy needs of these countries. The industrialized countries could consider providing means of transferring technologies more quickly to developing countries and could also offer some incremental financial assistance for their implementation.

On the other hand, developing countries can contribute by controlling the growth of energy demand (often linked to the population growth) and by making the most of their resources, particularly natural resources such as forests which absorb CO_2.

The challenge for industrialized and developing countries is to co-operate in the decision making process, system planning, technology development and implementation, and joint financing of energy strategies that will help achieve the common objective of these countries.

In some developing countries, massive investment in power capacity is required; this should be linked with the search for sustainable development. The concept of joint implementation is therefore very important and, if it is based on a bilateral and commercial basis, it may be possible to procure the vast sums required.

The international organizations working together in the DECADES project should consider making an inventory of issues affecting both industrialized and developing countries. Such an inventory would increase the possibilities of co-operation between both groups of countries by enhancing the transfer of information among countries.

FINANCING OF ENERGY STRATEGIES

The dilemma with which industrial projects are often faced is that a 'win–win' project is difficult to finance. On the basis of an analysis of the situation, it is possible to identify exactly which part of the process should be improved and how this improvement should be achieved, for example by using energy efficient technologies or improving maintenance and operation procedures. The problem then is to procure the funds required for these improvements, and this is where the dilemma arises. If the improvements actually lead to a 'win–win' situation, the improved process will be cleaner and more efficient and will lead to production cost savings. However, if there are cost savings, then the international community is extremely reluctant to provide funds, since improvements can be financed by the cost savings. The rules and regulations are such that it is easier to obtain funds for inefficient industrial plants than for efficient plants, because efficient and cost-effective plants achieve cost savings, so that no financing assistance seems to be necessary. Therefore, modellers should find ways to present a good project so that it will attract international grants.

THE DECISION MAKERS AND THE WAY OF COMMUNICATING WITH THEM

On the one hand, the Governments are the decision makers. On the other hand, Governments are elected by the public, and the extent to which the public and the interested and affected parties take part in the decision making process has an influence on the way in which the experts carry out analyses and present results. Therefore, the range of decision making processes should be broadened, and the highly formalized way of decision making should be changed to a way that makes more participation in decision making possible.

The information should be directed not only to environmental or policy groups for energy or economy but also to the decision makers in public authorities and utilities. It is the managers of utilities who make the investment decisions and they are the ones who have to be persuaded. The purpose of modelling is to assist the decision makers in public authorities and utilities. However, the key actors remain the regulators, not the managers of utilities. For instance, a utility cannot afford to internalize costs if other utilities are not prepared to do the same. Regulators are therefore needed and, if the power sector has a monopoly, then they have to decide whether and how the internalized costs should be reflected in the tariffs.

Although several good studies have been made, it appears that the results of these studies have not been used by decision makers as much as analysts would have wished. Thus, more work has to be done in order to increase the effectiveness of the ways in which the results are presented.

There is the risk that a decision maker who has a constituency demanding a certain decision might not look for the right information, i.e. the scientifically correct message, but for analytical results that justify his decision. The data and analyses developed by experts, such as those presented at this Symposium, might be discredited because of the large amount of money involved. Therefore, it is necessary to understand how the information will be used, and to attempt to present the data and analyses in such a way that the integrity of the message is preserved while meeting the needs of decision makers for proper information.

Although numerous models are available, they might not provide clearly understandable and usable information to decision makers. The analysis capabilities that have been developed are reasonably good, but decision makers need more concrete/operational suggestions and guidance on technology choices and policy measures that address the social, economic and resource management issues for a given country or region. Many models have been used for case studies and pilot projects, and this is certainly very useful in helping countries to implement comparative assessment as a kind of capacity building measure. However, the analysts are the ones who run the models, while decision makers are looking for usable information from the analysts. Decision makers, whether in Governments or utilities and whether in industrialized or developing countries, need very clear information and guidance, based on scientific findings from comparative assessment studies. Therefore, international organizations and the participants of the DECADES project might consider establishing an agreed framework within which guidance and suggestions for different regions or countries can be provided, taking into account their social and economic conditions and their capabilities to implement different technologies and policy measures.

COMMUNICATION WITH INTERESTED AND AFFECTED PARTIES/MEDIA

Criticism has been expressed concerning the fact that information is often addressed mainly to experts in the field of comparative assessment. Such information should be accessible to and understandable by interested or affected parties who should be part of the decision making process. Although the focus of meetings such as this Symposium is on scientific issues and information, efforts should be made to provide the public as well as decision makers with important information. Integrated assessment frameworks should focus on translating scientific and technical information into relevant guidance for decision makers. A typical example that illustrates the necessity of not only having scientifically correct information but also presenting this information properly is the controversy about the proposed sinking of the Brent Spar oil platform in the North Sea.

The capacity to produce models has been developed and analysts have been trying to communicate the results to decision makers; however, no effective communication mechanism has been found yet. Communication is a two-way process. A large amount of information is produced by analysts, but the communication of this information is not very efficient. Analysts might consider developing a tool for communicating with the public and promoting the use of comparative assessment in the decision making process together with intergovernmental organizations. An example of such a joint effort is the experience of Ontario Hydro in Canada.

In the DECADES project, this issue is also addressed; a reference book is being prepared that will help to bring together the results of the work on modelling and on the way of assisting decision makers. The initiators of the project also recognized that it is necessary to understand the viewpoints of the interested and affected parties and the issues that are of concern to them, and that it is not sufficient just to sell the results of the analyses to them. Rather than having a dialogue taking place between analysts, the policy makers and decision makers as well as interested and affected parties also have to be included in the discussions. This is a totally new dimension and an implementation process has to be built up. The DECADES reference book emphasizes this process of building consensus between interested and affected parties and decision makers.

Another example is the experience of the United States Department of Energy in handling the problem of addressing decision makers as well as policy makers. Analysts do not see themselves as public information people. Therefore, a 'wholesale' of information might be helpful in which the press and secondary users of the information communicate in a way that makes it easy for the public to understand the information. Communicating with the public means reaching two groups of people. The first target audience is the policy makers; these are the people who discuss the issues with the decision makers. These might challenge some results of the analysts, but the results should be presented in a way that ensures their objectivity. At the same time, by communicating with the public, the constituency of the decision makers, namely the tax payers, is also reached. Therefore, it is extremely important to focus on the way in which the information can be made more usable and more understandable by the public. This is a difficult task since the message should not be oversimplified in order not to lose accuracy.

The amount of information becoming available now is so large that it requires some kind of structure that can be used to understand and digest it. A possible solution that has been mentioned would be to establish a kind of independent and international advisory committee, such as the International Commission on Radiological Protection (ICRP). This committee should be generally recognized and should be able to provide undisputed values for some of the key impacts of electricity generation on the environment and on health. While the message should be as simple as possible, it should be authoritative so that there will be no discussion about its correctness. This might be a positive contribution to this important issue. The forum of exchange offered by the World Energy Council might also play an important role, since it has access to most utilities and can ensure continuous communication between them.

Nevertheless, there has been a tremendous evolution in activities addressing the issue of public involvement. Large changes have taken place in the attitudes and views regarding public involvement and major decisions concerning capital investments. This is an important issue that still needs to be addressed, but progress in the process of public involvement has been made in the last twenty years.

THE ROLE OF NUCLEAR POWER IN ALLEVIATING GREENHOUSE GAS EMISSIONS

The role of nuclear power in alleviating greenhouse gas emissions, especially in developing countries, has to be demonstrated. Regarding future strategies aiming at mitigating emissions of greenhouse gases, the role of nuclear power is not unanimously recognized by opponents to nuclear power who believe that there are still unresolved issues, such as safety, nuclear proliferation and waste disposal. This is illustrated by the difficulties in assessing and reaching a consensus on the role of nuclear power as an option for alleviating greenhouse gas emissions facing the Working Group III of the Intergovernmental Panel on Climate Change dealing with the Second Assessment Report.

Many case studies have shown that nuclear power can play an important role in reducing greenhouse gas emissions and emissions of other pollutants from the power sector. The question remains how to facilitate the implementation of nuclear power programmes, especially in developing countries.

The externalities of nuclear power can be assessed competently, and the figures presented at this Symposium do not differ from those developed by international organizations. There is, of course, much controversy about waste disposal and severe accidents. For waste disposal, conceptual and technical solutions are available. Numerous painstaking studies have been carried out in laboratories and at test sites, as well as in natural analogues; these studies show that radioactive wastes can be safely managed and disposed of, whereas for many other types of waste it has not even been attempted to find a way of disposal. With regard to nuclear accidents, public aversion and the risk of investors are important aspects. If we are to use the nuclear option, which does have advantages, it is inevitable to acknowledge Governments as the insurers of last resort. This is obviously an externality; the actuarial risk is extremely low, according to past experience, but a better assessment of the estimated risk and its appraisal by the public is needed.

INTERNALIZATION OF EXTERNAL COSTS

There are concerns regarding the difficulty of presenting the fact that there is a lack of good scientific and technical information on some issues or that the analytical tools being used cannot produce definitive answers to certain problems. In particular, the ExternE project pointed out that many uncertainties are involved in the valuation of external costs of energy systems.

A stage has been reached where the existence of external costs has been more or less acknowledged. Five or ten years ago, there were very divergent views and large conflicts and debates. Today, a framework for reaching a consensus exists on external costs — perhaps not on the issue of climate change but on other issues. Regarding climate change, a consensus exists on the data, which means that the next step would be to launch case studies in order to demonstrate the internalization of external costs, to identify the best tools and to test their efficiency.

The first difficulty with internalization is that most of the local and regional impacts are dependent on the site, and therefore a general internalization of the costs is not possible; internalization has to be done individually at the different sites.

Other difficulties are the way of dealing with uncertainties, the acceptance of the risks involved in the uncertainty associated with the evaluation, and the acceptance of the necessary financing of internalization of externalities. The problems in developing and industrialized countries are different. Since industrialized countries use much more energy than developing countries, it might be appropriate for them to pay more; this is, however, a political issue. Internalization, which is a useful goal, will be very difficult to achieve, especially with regard to local and regional impacts.

The results that can be obtained depend on the choice of technology (the choice between different technologies as well as the varying levels of upgrades of the same technology) and on the site conditions. For the same technology or the same process applied in different places, different results with regard to externalities will be obtained.

Another issue that has to be dealt with is the environmental effects of a restructured industry. It is very unclear what restructuring would mean for the environment. In terms of the cost of electricity, restructuring will be very beneficial to the consumer, at least in some countries; however, it is not at all clear what restructuring implies in terms of environmental impacts and particularly in terms of externalities.

In the discussion of the cultural context of the analyses and options the issue of a carbon tax was mentioned; there seems to be an inherent assumption that carbon taxes have been and will continue to be unpopular. In some countries, for instance Denmark, people do not object to paying a carbon tax, any more than objecting to paying a tax to support the police, schools or hospitals, or to contribute to international organizations. Carbon taxes are not necessarily unpopular.

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Session 2	M. MUNASINGHE	Sri Lanka
Session 3	K. YEAGER	United States of America
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Session 5	C. CORDOBA SALAZAR	Colombia
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M. DEMIR	Proceedings Editor (IAEA)

LIST OF PARTICIPANTS

Abtahi, M.	United Nations Educational, Scientific and Cultural Organization, Liaison Office in Vienna (D1231), Wagramerstrasse 5, A-1400 Vienna, Austria
Abu Qayyas, M.M.	Ministry of Energy and Mineral Resources, P.O. Box 140027, Amman, Jordan
Adewole, S.	Organization of Petroleum Exporting Countries, Obere Donaustrasse 93, A-1020 Vienna, Austria
Ajuria, G.	Permanent Mission of Mexico, Türkenstrasse 15, A-1090 Vienna, Austria
Aktürk, S.	Technology Department, Turkish Atomic Energy Authority, Lodumlu, TU-06530 Ankara, Turkey
Al-Alao, S.	Ministry of Electricity, P.O. Box 4900, Damascus, Syrian Arab Republic
Alawaji, S.H.	Energy Research Institute, KACST, P.O. Box 6086, Riyadh 11442, Saudi Arabia
Amann, N.	International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria
Babaev, N.S.	Ministry of the Russian Federation for Atomic Energy, Staromonetny pereulok 26, 109 180 Moscow, Russian Federation
Balajka, J.	Profing Company Limited, Bajkalska 27, SK-82721 Bratislava, Slovakia

Barakat, M.F.	Arab Atomic Energy Agency, P.O. Box 402, Al Menzah 1004, Tunis, Tunisia
Belovic, V.	Ministry of the Environment of the Slovak Republic, Hlboka 2, SK-81235 Bratislava, Slovakia
Bennett, L.	Planning and Economic Studies Section, Division of Nuclear Power, International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
Berry, J.E.	ETSU, Harwell, Didcot, Oxfordshire, OX11 0RA, United Kingdom
Bertel, E.	Nuclear Development Division, Nuclear Energy Agency of the OECD, Le Seine Saint-Germain, 12, Boulevard des Iles, F-92130 Issy-les-Moulineaux Cedex, France
Bérubé, G.	Hydro Québec, 75, Boulevard Réné-Lévesque, Montreal, Quebec H2Z 1A4, Canada
Bestebroer, S.I.	KEMA, P.O. Box 9035, NL-6800 Arnhem, Netherlands
Blix, H.	International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
Borra, T.M.	Department of Energy, PNPC Complex, Merrit Road, Fort Bonifacio, Metro Manila, Philippines
Brea Alvarez, M.	Unidad Electrica S.A., Francisco Gervás 3, E-28020 Madrid, Spain
Campo, R.	AA 21585 Bogota, DC, Colombia

Capros, P.	National Technical University of Athens, 42, Patission Street, GR-10682 Athens, Greece
Cardona Alvarez, J.	Interconexion Electrica S.A., Calle 12 Sur No. 18–168, El Poblado, Medellin, Colombia
Chadwick, M.J.	Stockholm Environment Institute, P.O. Box 2142, S-10314 Stockholm, Sweden
Chen, Changhe	Bureau of International Co-operation, China Atomic Energy Authority, P.O. Box 2101, Beijing 10082, China
Chen, Zhuzhou	Bureau of Safety, Protection and Health, China Atomic Energy Authority, P.O. Box 2101–14, Beijing 10082, China
Chernilin, Yu.F.	Department of Nuclear Power, Economics and Planning, Institute of Nuclear Reactors, Russian Research Centre, Kurchatov Institute, Kurchatov Square 1, 123182 Moscow, Russian Federation
Contaxis, G.C.	Department of Electrical and Computer Engineering, National Technical University of Athens, 42, Patission Street, GR-10682 Athens, Greece
Conzelmann, G.	Division of Decision and Information Sciences, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439/4832, United States of America
Cordoba Salazar, C.	Unidad de Planeación Minero-Energética, Ministerio de Minas y Energía, Avda. 40a No. 13–09, AA 21585 Bogota, DC, Colombia

Corregidor Sanz, D.
Unidad Electrica S.A.,
Francisco Gervás 3,
E-28020 Madrid, Spain

Dai, Lin
Energy Research Institute,
State Planning Commission,
Zahnsimen, Shahe, Changping County,
102206 Beijing, China

Das, A.
Tata Energy Research Institute,
Darbari Seth Block,
Habitat Place, Lodi Road,
New Delhi 110003, India

De Millas, R.
KFW,
Palmengartenstrasse 5-9,
D-60325 Frankfurt, Germany

Delvoye, J.
TRACTEBEL,
Ave. Ariane 7,
B-1200 Brussels, Belgium

Derrough, M.
Planning and Economic Studies Section,
Division of Nuclear Power,
International Atomic Energy Agency,
P.O. Box 100, A-1400 Vienna, Austria

Dobrusin, A.
Instituto de Economía Energética,
12 de Octubre 1915, CC 138,
8400 San Carlos de Bariloche, Argentina

Draxler, R.
Technische Universität Graz,
Inffeldgasse 18,
A-8010 Graz, Austria

Duchemin, P.
Electricité de France,
2, rue Louis Murat,
F-75008 Paris Cedex, France

Dutkiewicz, R.K.
Energy Research Institute,
University of Cape Town,
P.O. Box 207,
7800 Plumstead, South Africa

Ellis, J.	Energy and Environment Division, International Energy Agency, 2, rue André Pascal, F-75775 Paris Cedex 16, France
Feretic, D.	Faculty of Electrical Engineering and Computing, Department of Power Systems, Unska 3, CR-41000 Zagreb, Croatia
Ferraris, M.M.	Permanent Mission of the Holy See to the IAEA, Theresianumgasse 33/4, A-1040 Vienna, Austria
Fritsche, U.R.	Öko-Institut e.V., Bunsenstrasse 14, D-64293 Darmstadt, Germany
Gaal, P.	National Institute of Hygiene and Epidemiology, Trnavská 52, SK-82108 Bratislava, Slovakia
García, B.M.	Nuclear Energy Information Centre, Calle 20, No. 4111, esq. 47 Playa, Havana, Cuba
Geeraert, B.E.A.	Electrabel NV, Department BMT, Regentlaan 8, B-1000 Brussels, Belgium
Geidl, J.	Office of Coal, Nuclear, Electric and Alternate Fuels, Energy Information Administration, United States Department of Energy, EI-50, 1000 Independence Avenue, SW, Washington, DC 20585, United States of America
Gilling, J.	Efficiency and Household, Fuels, Industry and Energy, The World Bank, 1818 H Street, NW, Washington, DC 20433, United States of America
Gomes, E.B.P.	National Nuclear Energy Commission, Rua General Severiano 90, Botafogo, 22283-900 Rio de Janeiro, Brazil

Gray, J.	British Nuclear Fuels plc, Hinton House, H479, Risley, Warrington, Cheshire WA3 6AS, United Kingdom
Gröndalen, O.	Sydkraft Konsult, S-205090 Malmö, Sweden
Guindon, S.D.	Electricity Branch Department, Natural Resources Canada, 580 Booth Street, Room 1927, Ottawa, Ontario K1A 0E4, Canada
Gurkok, C.	United Nations Industrial Development Organization, P.O. Box 300, A-1400 Vienna, Austria
Hamilton, B.	Division of Nuclear Power, International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
Heaps, C.	Tellus Institute, Stockholm Environment Institute–Boston Center (SEI-B), 11, Arlington Street, Boston, MA 02116, United States of America
Hein, W.	Bundeskanzleramt, Hohenstaufengasse 3, A-1010 Vienna, Austria
Herberg, T.C.	Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Dag-Hammarskjöld-Weg 1-5, D-65760 Eschborn, Germany
Hirschberg, S.	Paul Scherrer Institute, Würenlingen and Villigen, CH-5232 Villigen, Switzerland
Hoffer, J.	Computer and Automation Research Institute, P.O. Box 63, H-1518 Budapest, Hungary
Holzer, H.P.	Österreichische Elektrizitätswirtschafts AG, Am Hof 6 A, A-1010 Vienna, Austria

Hongisto, M.Y.	Environmental Protection Division, Imatran Voima Oy, SF-01019 Ivo, Finland
Horváth, I.	Biological Department, The Real Green Club, Istenhegyi ut 35/a, H-1125 Budapest, Hungary
Iotova, A.	National Institute of Meteorology and Hydrology, Bulgarian Academy of Sciences, Blvd Tsarigradsko Chaussee 66, BG-1784 Sofia, Bulgaria
Ismail, I.A.H.	Energy Section, Organization of Petroleum Exporting Countries, Obere Donaustrasse 93, A-1020 Vienna, Austria
Ivanusic, A.	JP EGS-ri, d.d. Vetrinjska 2, SL-62000 Maribor, Slovenia
Jaime-Paredes, A.	Comisión Federal de Electricidad, Melchor Ocampo 469, piso 8, Col. Nueva Anzures, 11590 Mexico, D.F., Mexico
Jameel, M.	Permanent Mission of Pakistan to the IAEA, Hofzeile 13, A-1190 Vienna, Austria
Jin, Youcai	Permanent Mission of China to the IAEA, Steinfeldgasse 1, A-1190 Vienna, Austria
Juhn, Poongeil	Division of Nuclear Power, International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
Kalliauer, A.	Österreichische Elektrizitätswirtschafts AG, Am Hof 6 A, A-1010 Vienna, Austria

Kanhouwa, S.	Energy Information Administration, United States Department of Energy, EI-532, 1000 Independence Avenue, SW, Washington, DC 20585, United States of America
Katyshev, S.I.	Division of Science, New Technologies and Environmental Protection, Ministry of Energy and Coal Industry, ul. Bogenbany Batyr, 142, Almaty 480091, Kazakhstan
Keddar, F.	Université d'Oran, Institut de Physique, Oran Es-Senia 32000, Algeria
Khan, A.M.	Applied Systems Analysis Group, Pakistan Atomic Energy Commission, P.O. Box 1114, Islamabad, Pakistan
Khatib, H.	Honorary Vice Chairman, World Energy Council, P.O. Box 925387, Amman, Jordan
Kienzl, K.	Umweltbundesamt Wien, Spittelauer Lände 5, A-1090 Vienna, Austria
Kim, H.J.	Korea Atomic Energy Research Institute, P.O. Box 105, Yuseong, 305-353 Taejon, Republic of Korea
Kim, J.S.	Organization for Korea Atomic Energy Awareness, 1443-15, Seocho-Dong, Seocho-ku, Seoul, Republic of Korea
Klik, F.	Nuclear Research Institute, CZ-25068 Řež, Czech Republic
Klimbacher, J.	Kärntner Elektrizitätswerke AG, Arnulfplatz 2, A-9020 Klagenfurt, Austria

Köhler, W.H.	United Nations Industrial Development Organization, P.O. Box 300, A-1400 Vienna, Austria
Kononov, S.L.	Department of Nuclear Power, Economics and Planning, Institute of Nuclear Reactors, Russian Research Centre, Kurchatov Institute, Kurchatov Square 1, 123182 Moscow, Russian Federation
Krewitt, W.	Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart, Hessbrühlstrasse 49a, D-70565 Stuttgart, Germany
Kromp-Kolb, H.	Forum für Atomfragen, Türkenschanzstrasse 17/8, A-1180 Vienna, Austria
Lanari, R.	Makivik Corporation, 650 32e Avenue, Lachine, Quebec H8T 3K5, Canada
Larsson, T.	Energy Systems Technology, Chalmers University of Technology, S-412 96 Göteborg, Sweden
Latek, S.W.	National Atomic Energy Agency, ul. Krucza 36, PL-00-921 Warsaw, Poland
Laue, H.J.	Fachinformationszentrum Karlsruhe, Gesellschaft für wissenschaftlich-technische Information mbH, Postfach 2465, D-76012 Karlsruhe, Germany
Layr, P.	EVN Energie-Versorgung Niederösterreich AG, Johann Steinböck-Strasse 1, A-2344 Maria Enzersdorf-Südost, Austria
Leal, J.	CIEMAT, Instituto de Estudios de Energía, Avda Complutense 22, E-28040 Madrid, Spain

Leca, A.	Polytechnical University, Splaiul Independentei 313, Sector 5, RO-77206 Bucharest, Romania
Lee, Chinmin	World Health Organization, Vienna International Centre, Wagramerstrasse 5, A-1400 Vienna, Austria
Lefevre, T.	Economic and Social Commission for Asia and the Pacific (ESCAP), Asian Institute of Technology (AIT), P.O. Box 2754, 10501 Bangkok, Thailand
Lehrhofer, J.G.	Institut für Hochspannungstechnik, Technische Universität Graz, Krennagasse 37Í, A-8010 Graz, Austria
Leydon, K.	Directorate General for Energy (DG XVII), European Commission, 200, rue de la Loi, B-1049 Brussels, Belgium
Liu, Zunqi	Permanent Mission of China to the IAEA, Steinfeldgasse 1, A-1190 Vienna, Austria
Mackenzie, G.	UNEP Collaborating Centre on Energy and Environment, Systems Analysis Department, Risø National Laboratory, P.O. Box 49, DK-4000 Roskilde, Denmark
Mair, N.	Oberösterreichische Kraftwerke AG, Böhmerwaldstrasse 3, A-4020 Linz, Austria
Malbasa, N.	Energy Systems and Environmental Protection Department, EKONERG Ltd, Ulica grada Vukovara 37, CR-41000 Zagreb, Croatia

Manafi, J.	Gharb Thermal Power Plant Project, TAVANIR, Iran Electric Organization, Yasemi Street, Vali-Asr Avenue, Tehran, Islamic Republic of Iran
Markandya, A.	Harvard Institute for International Development, Harvard University, Cambridge, MA 02138, United States of America
Marques, B.	Companhia Energética de Minas Gerais, 30161-970 Belo Horizonte, Brazil
Martinsen, D.	Forschungszentrum Jülich GmbH, Postfach 1913, D-52425 Jülich, Germany
Messner, S.	International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria
Mikhalevich, A.A.	Institute of Power Engineering Problems, Belarus Academy of Sciences, Sosny, 220109 Minsk, Belarus
Mirasgedis, S.	National Technical University of Athens, 9, Heroon Polytechniou, Zografou Campus, GR-15780 Athens, Greece
Moon, K.H.	Korea Atomic Energy Research Institute, P.O. Box 105, Yuseong, 305-353 Taejon, Republic of Korea
Morici, A.	Italian National Agency for Environmental Protection, Via Brancati 48, I-00144 Rome, Italy
Morris, S.C.	World Health Organization Collaborating Centre on Health and Environmental Effects of Energy Systems, Biomedical and Environmental Assessment Group, Building 490D, Brookhaven National Laboratory, Upton, Long Island, NY 11973, United States of America

Müller, T.	Verband der Elektrizitätswerke Österreichs, Brahmsplatz 3, A-1040 Vienna, Austria
Munasinghe, M.	University of Colombo, 10 De Fonseka Place, Colombo 5, Sri Lanka
Nazemi, A.	United Nations Industrial Development Organization, P.O. Box 300, A-1400 Vienna, Austria
Ndao Rilogue, A.	Ministère des mines, de l'énergie et du pétrole, B.P. 874, Libreville, Gabon
Nicholls Estrada, C.	Interconexion Electrica S.A., Calle 12 Sur No. 18–168, Apartado Aereo 8915, Medellin, Colombia
Noviello, L.	Nuclear Energy Division (ATN), ENEL Società per Azioni, Viale Regina Margherita 137, I-00198 Rome, Italy
Oduwo, R.N.	National Council for Science and Technology, P.O. Box 30623; Nairobi, Kenya
Olsson, L.E.	World Climate Programme Department, World Meteorological Organization, 41, Avenue Giuseppe-Motta, CH-1211 Geneva 2, Switzerland
Ossoucah, Ph.	Ministère des mines, de l'énergie et du pétrole, B.P. 874, Libreville, Gabon
Pachauri, R.K.	Tata Energy Research Institute, Darbari Seth Block, Habitat Place, Lodi Road, New Delhi 110 003, India
Paga, E.	Organization of Petroleum Exporting Countries, Obere Donaustrasse 93, A-1020 Vienna, Austria

Palige, J.	Institute of Nuclear Chemistry and Technology, Department VI, ul. Dorodna 16, PL-03-195 Warsaw, Poland
Park, S.S.	Organization for Korea Atomic Energy Awareness, 1443-15, Seocho-Dong, Seocho-ku, Seoul, Republic of Korea
Pendergast, D.R.	Atomic Energy of Canada Ltd, Sheridan Park Research Community, Mississauga, Ontario L5K 1B2, Canada
Perharic, H.	Energy Systems and Environmental Protection Department, EKONERG Ltd, Ulica grada Vukovara 37, CR-41000 Zagreb, Croatia
Perrakis, K.	Department of Electrical and Computer Engineering, National Technical University of Athens, 42, Patission Street, GR-10682 Athens, Greece
Pochman, W.	Organization of Petroleum Exporting Countries, Obere Donaustrasse 93, A-1020 Vienna, Austria
Pop-Jordanov, J.	Research Centre for Energy and Informatics, Macedonian Academy of Sciences and Arts, P.O. Box 428, 91000 Skopje, The Former Yugoslav Republic of Macedonia
Pop-Jordanova, N.	Faculty of Medicine, University of Skopje, Vodnjanska 17, 91000 Skopje, The Former Yugoslav Republic of Macedonia
Popescu, A.	Institute of Power Studies and Design, 1, Lacul Tei Blvd, RO-77206 Bucharest, Romania
Popovici, D.	Institute of Power Studies and Design, 1, Lacul Tei Blvd, RO-77206 Bucharest, Romania

Ragette, G. Central Institute for Meteorology and Geodynamics,
Hohe Warte 38,
A-1190 Vienna, Austria

Rahman, F. Organization of Petroleum Exporting Countries,
Obere Donaustrasse 93,
A-1020 Vienna, Austria

Rao, K. Organization of Petroleum Exporting Countries,
Obere Donaustrasse 93,
A-1020 Vienna, Austria

Rashad, S.M. Atomic Energy Authority,
101, Kasr el Eini Street,
Cairo, Egypt

Reuber, B. Environment and Sustainable Development Division,
Business/Environment Integration Department,
Ontario Hydro,
700 University Ave., H18 J15,
Toronto, Ontario M5G 1X6, Canada

Reuter, A.L. Drauconsulting GmbH,
Kohldorfer Strasse 98,
A-9020 Klagenfurt, Austria

Roturier, J. Université de Bordeaux,
Centre d'études nucléaires de Bordeaux-Gradignan,
B.P. 120,
F-33175 Gradignan Cedex, France

Saburido, E.H.F. Permanent Mission of Cuba to the IAEA,
Himmelhofgasse 40 a-c,
A-1130 Vienna, Austria

Schleisner, L. Risø National Laboratory,
P.O. Box 49,
DK-4000 Roskilde, Denmark

Schlenzig, C. Institut für Energiewirtschaft
und rationelle Energieanwendung,
Universität Stuttgart,
Pfaffenwaldring 31,
D-70565 Stuttgart, Germany

Seidel, H.	United Nations Industrial Development Organization, P.O. Box 300, A-1400 Vienna, Austria
Semenov, B.A.	Department of Nuclear Energy and Safety, International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
Shelton, R.B.	Energy Division, Martin Marietta Energy Systems, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 31831-6205, United States of America
Silny, M.	Ministry of the Environment of the Slovak Republic, Hlboka 2, SK-812 35 Bratislava, Slovakia
Siniak, Y.	International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria
Song, Kidong	Economic Analysis Department, Korea Atomic Energy Research Institute, P.O. Box 105, Yuseong, Daeduk-Danji, 305-600 Taejon, Republic of Korea
Sørensen, B.	Institute of Studies in Mathematics and Physics, Roskilde University, P.O. Box 260, DK-4000 Roskilde, Denmark
Starfelt, N.G.	Nuclear Training and Safety Centre, P.O. Box 1039, S-611 29 Nyköping, Sweden
Steinhäusler, F.	Institut für Physik und Biophysik, Universität Salzburg, Hellbrunnerstrasse 34, A-5020 Salzburg, Austria
Stern, R.	Industry and Energy Department, The World Bank, 1818 H Street NW, Washington, DC 20433, United States of America

Stevens, G.	Nuclear Development Division, Nuclear Energy Agency of the OECD, Le Seine Saint-Germain, 12, Boulevard des Iles, F-92130 Issy-les-Moulineaux Cedex, France
Sudja, Nengah	Indonesia Electric State Company, Electric System Planning, Jl. Duren Tiga, Djakarta 12760, Indonesia
Tamizrad, J.	Gas Turbine Division, TAVANIR, Iran Electric Organization, Yasemi Street, Vali-Asr Avenue, Tehran, Islamic Republic of Iran
Tavoni, R.	ENEA, Via Martiri di Monte Sole 4, I-40129 Bologna, Italy
Tcheknavorian-Asenbauer, A.	Industrial Sectors and Environment Division, United Nations Industrial Development Organization, P.O. Box 300, A-1400 Vienna, Austria
Telfer, J.	Scottish Nuclear Limited, 3 Redwood Crescent, Peel Park, East Kilbride, Glasgow, G74 5PR, United Kingdom
Tomsic, Z.	Faculty of Electrical Engineering and Computing, Unska 3, CR-41000 Zagreb, Croatia
Tort, V.	Centre d'étude sur l'évaluation de la protection dans le domaine nucléaire (CEPN), B.P. 48, F-92263 Fontenay-aux-Roses Cedex, France
Twardy, L.	Polish Power Grid Company, ul. Mysia 2, PL-00 496 Warsaw, Poland
Uchiyama, Y.	Socioeconomic Research Centre, Central Research Institute of the Electric Power Industry, 1-6-1 Ohtemachi, Chiyoda-ku, Tokyo 100, Japan

Urli, N.B.	Rudjer Boskovič Institute, Bijenicka 54, CR-41000 Zagreb, Croatia
Vajda, G.	Hungarian Atomic Energy Commission, Margit blvd 85, H-1024 Budapest, Hungary
Valette, P.	Directorate General for Science, Research and Development (DG XII), European Commission, 200, Rue de la Loi, B-1049 Brussels, Belgium
Vana, N.	Atominstitut der Österreichischen Universitäten, Schüttelstrasse 115, A-1020 Vienna, Austria
Varol, G.	Research Planning and Co-ordination Department, Turkish Electricity Generation and Transmission Corporation, Inonu Bulvari 27/18, TU-06530 Ankara, Turkey
Veleva, B.	National Institute of Meteorology and Hydrology, Bulgarian Academy of Sciences, Blvd Tsarigradsko Chausee 66, BG-1784 Sofia, Bulgaria
Vielle, M.	Service des études économiques, Direction de la stratégie et de l'évaluation, Commissariat à l'énergie atomique, Centre d'études nucléaires de Saclay, F-91191 Gif-sur-Yvette Cedex, France
Vilemas, J.	Lithuanian Energy Institute, Breslaujos Street 3, LT-3035 Kaunas, Lithuania
Villela, N.P.	Departamento de Meio Ambiente, Furnas Centrais Elétricas S.A., Rua Real Grandeza, 219 — Botafogo, 22283-900 Rio de Janeiro, Brazil

Vladu, I.F.	Planning and Economic Studies Section, Division of Nuclear Power, International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
Voss, A.	Institut für Energiewirtschaft und rationelle Energieanwendung, Universität Stuttgart, Hessbrühlstrasse 49a, D-70565 Stuttgart, Germany
Wald, F.	Electricité de France, Direction de l'équipement, 22-30, avenue de Wagram, F-75382 Paris Cedex 08, France
Weimann, G.H.	Österreichisches Forschungszentrum Seibersdorf GmbH, A-2444 Seibersdorf, Austria
Wertelaers, A.	Ministère de l'emploi et du travail, Service SSTIN, Rue Belliard 51-53, B-1040 Brussels, Belgium
Wicklein, W.	United Nations Industrial Development Organization, P.O. Box 300, A-1400 Vienna, Austria
Wikdahl, C.E.	Energiforum AB, Allhelgonavägen 25, S-611 35 Nyköping, Sweden
Williams, R.	United Nations Industrial Development Organization, P.O. Box 300, A-1400 Vienna, Austria
Wilson, R.	Harvard University, 17 Oxford Street, Cambridge, MA 02138, United States of America
Wolloner, R.	Österreichische Elektrizitätswirtschafts AG, Am Hof 6 A, A-1010 Vienna, Austria
Yagan, M.	Ministry of Energy and Mineral Resources, P.O. Box 140027, Amman, Jordan

Yeager, K.	Electric Power Research Institute, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303, United States of America
Youssef, A.R.	Public Establishment of Electricity GT, P.O. Box 42, Banias, Syrian Arab Republic
Zaleski, P.	Centre de géopolitique de l'énergie et des matières premières, Place du Maréchal de Lattre de Tassigny, F-75775 Paris Cedex 16, France
Zgura, G.	Polytechnical University, Splaiul Independentei 313, Sector 5, RO-77206 Bucharest, Romania
Zhang, Huazhu	China Atomic Energy Authority, P.O. Box 2101, Beijing 100822, China
Zhou, Dadi	Energy Research Institute, State Planning Commission, Zhansimen Road, Gronghna Town, Chang Ping County, Beijing 102206, China

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