Energy Vol. 16, No. 10, pp. 1215–1224, 1991
Printed in Great Britain.

0360-5442/91 $3.00 + 0.00

COST-EFFECTIVENESS ANALYSIS OF AIR-POLLUTION CONTROL MEASURES

Alfred Voß and Günter Schmid

Institute for Energy Economics and the Rational Use of Energy
University of Stuttgart, Pfaffenwaldring 31, W-7000 Stuttgart 80, FRG

(Received 18 April 1991)

Abstract - We describe a strategy for dealing with the challenges of air pollution and climate change capable of adaptation to improved scientific knowledge in the future. The analytical framework for identifying efficient control strategies is described and selected results of cost-effective methods to control SO_2, NO_x and CO_2 emissions are discussed.

1. INTRODUCTION

The eighties saw the emergence of the environmental challenge and a growing concern about man's potential to destroy the natural environment through his own activities. The scope of concerns is broad and includes air pollution, water quality, waste disposal, the use of toxic substances, land use, and siting issues. In recent years, the potential altering of the earth's climate has gained special attention. As far as air pollution and climate change are concerned, the conversion and use of energy is the single most important anthropogenic source of gaseous pollutants and greenhouse gases. The combustion of fossil fuel supplying nearly 90% of the world's energy needs is the main source of SO_2 and NO_x emissions contributing to the acidification of soil and lakes, to forest, crop and material damages, and to human-health deterioration. In addition, fossil-fuel combustion is the principal source of anthropogenic CO_2 emissions, which are believed to be responsible for about half of the man-made greenhouse effect. Another of the energy-related greenhouse gases is methane, which accounts for about 19% of this effect.

As shown in Table 1,[1] energy-related emissions of air pollutants within the European Community (EC) are in the range of 13 Mtons of SO_2 and 10 Mtons of NO_x. Power generation is the main contributor to SO_2 emissions and about half of the NO_x emissions stem from the transport sector. The SO_2 and NO_x emissions in member countries of the EC follow different trends. With the introduction of SO_2-control techniques, the limitation of the sulphur content in fuels and the shift to nuclear power, SO_2 emissions in the EC as a whole have been decreasing over the last ten years, while NO_x emissions have remained nearly constant. With a total amount of 2600 Mtons of CO_2, the EC is responsible for about 13% of global CO_2 emissions.

It is important to note that due to differences in the economic situation, the primary energy mix, and the introduction of pollutant-control measures, the per capita emissions of SO_2, NO_x and CO_2 vary considerably among member countries of the EC.

Table 1. Energy-related emissions in the EC.

Mtons/a	1986	1990
SO_2	13.40	12.23
NO_x	9.56	10.38
CO_2	2560	2765

Energy production and energy use are the largest anthropogenic sources of greenhouse gases and other air pollutants. It is therefore likely that emission-control policies reducing the emissions of harmful trace gases to environmentally acceptable levels will have a severe impact on the energy system and hence on national economies. Preventive air-pollution control strategies appear to be extremely costly and will require additional quantities of scarce economic resources with considerable opportunity costs. The resulting changes in energy-use patterns can have large socio-economic, political and developmental effects.

From the policy-making point of view, air pollution and climate change have some common characteristics. The damages caused by air pollution and climate change are impossible to quantify with present-day knowledge. Little is known, for example, about the impact of climate change on agriculture, land use, forestry, natural terrestrial ecosystems, water resources, and human health, as well as on their regional distribution. Unless the existing uncertainties are not resolved, there is no sound basis for an assessment of the benefits of air-pollution control policies. There are considerable uncertainties about the necessary reduction requirements, as well as their temporal scope, to reach an environmentally and climatologically benign level. Moreover, due to the long-range transport of SO_2 and NO_x and the global distribution of greenhouse gases, effective control strategies would require a multinational or globally coordinated effort and a high degree of international cooperation.

As far as the emissions of SO_2 and NO_x are concerned, emission-reduction regulations, especially emission standards, have been enforced on a national and European level. In the protocols of Helsinki and Sofia, reduction targets for SO_2 and NO_x were agreed upon. It is still an open question, whether the resulting emission reduction of current legislation will be sufficient. There is some indication, based on the concept of critical loads for acidic deposition in Europe, that very substantial reductions in the emissions of SO_2 and NO_x will be required to achieve deposition levels below these loads in all sensitive areas. Such reductions go well beyond the committed emission reductions within the framework of the Long-Range Transport Convention.

Calls for reducing greenhouse-gas emissions have been a common theme at international conferences on global warming. For example, the final statement from the 1988 Toronto Conference on "The Changing Atmosphere" called for a 20% world-wide reduction of CO_2 emissions by the year 2005 and a 50% reduction by 2050. How these world-wide reduction targets are to be transformed into national reduction requirements is an unsolved issue. In any case, the major share of the reduction has to be accomplished by the industrialized countries.

The characteristics of air pollution and climate change present a serious dilemma to policy makers. Existing scientific uncertainties about the necessary emission-reduction targets, a lack of knowledge about the benefits of reducing the emissions of air pollutants and a lack of reliable information on the cost of emission abatement make it difficult to assess the feasibility of alternative reduction proposals and to identify a rational course of action. We argue that cost-effectiveness analysis can help to solve some of the decision-making issues and that it can help in developing a strategy for dealing with the air-pollution and climate change issues that will be capable of adapting to improved scientific knowledge in the future. The essence of such a strategy, identified by applying the cost-effectiveness approach, is to give first preference to those actions that can be justified without any need to consider the environmental benefits they provide. The second priority refers to low-cost options for which the benefits are potentially very large in relation to the costs of the option. Finally, if more stringent reduction targets are necessary to limit climate change and environmental impact to a tolerable level, higher cost options could be justified on a larger scale.

In the following sections, we first give a brief description of the cost-effectiveness approach and discuss the role of energy-environmental models in identifying efficient air-pollution and greenhouse-gas control strategies. Thereafter, some results of cost-effectiveness analysis to control emissions from the energy sectors are outlined and the limitations of the approach are discussed.

2. COST-EFFECTIVENESS ANALYSIS (CEA)

The cost-effectiveness analysis[2] starts from the fact that future damages related to air pollution can hardly be quantified. No environmental costs (cost for restauration of the environment) or benefits can be attributed to a strategy directly, since a damage function of trace-gas emissions is difficult to generate. Due to these difficulties, the CEA approach uses emission levels as a point of departure. For each emission level or emission target, a set of actions associated with minimum cost are determined. The final choice of actions, weighing costs and related achievable targets, is left to the decision maker. Policy makers need deep insight into the effects of alternative policy measures and their interference. First of all, they need complete information about the available technical options, their potentials (technical and economic), their costs, restrictions, and drawbacks. Each relevant option is characterized by its technical, economic and environmental parameters. This is the starting point of cost-effectiveness analysis. The following steps are necessary for a comprehensive cost-effectiveness analysis: (i) compilation and characterisation of all available measures; (ii) assessment of technologies and measures by their specific reduction costs (unit cost to improve the given target); (iii) quantification of their potentials today and in future; (iv) consideration of institutional, legislative and contractual restrictions; (v) separate assessment of measures; (vi) interaction of different measures (e.g. overlapping of potentials); (vii) ranking and general assessment of measures; (viii) efficient control strategies to reach a given reduction target; (ix) robustness of measures (sensitivity of ranking order and cost). The variety of measures, the complexity of the energy system and the need for projections and impact analysis suggest the use of an energy-system model. These models provide a straightforward approach to CEA.

3. THE CONSTRUCTION AND APPLICATION OF ENERGY MODELS

For decision support on a national level, energy-systems models were created to represent regional energy systems on an aggregated level. Fuels and technologies are modelled in an oriented network representation. The models that have been applied are EFOM, MARKAL and MESSAGE and use linear equations, constraints and objective. The target is to maximize or minimize a given objective function subject to a set of constraints and equations. The linkage between energy-conversion and end-use technologies and air pollution requires modeling of all relevant technologies. For the cost-effectiveness analysis of pollution-control options, the models use mainly discounted costs as the objective function. Sometimes the weighed sum of the emissions is taken. In Fig. 1, the network representation of an energy system model is displayed.

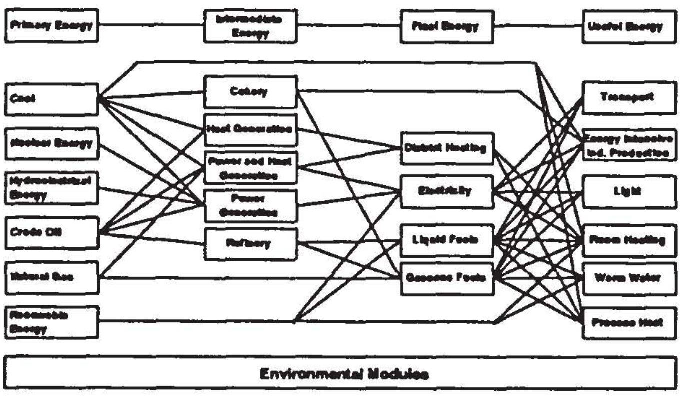

Fig.1. Energy flow network of models.

To use the model in the framework of a CEA, future emission levels are pre-defined and the optimization provides a set of measures achieving the given targets at least cost. The corresponding mix of technologies is called efficient. As emission levels are reduced, emission-control options enter the solution and the unit costs of emission control (marginal costs) increase. Thus, cost curves for the future control of emissions can easily be generated to account for the interference of measures. Emission-control options, which may be analyzed by using an optimization model, are substitution among fossil fuels and fuel-quality improvement, substitution for fossil by non-fossil fuels, energy conservation, combustion measures and flue-gas scrubbing (end-of-pipe technologies), reduction of useful energy demand (e.g. elasticities). A model provides an overview of these measures and technologies and allows their consistent analysis.

4. ILLUSTRATION OF CEA MODEL RESULTS

The CEA approach was successfully applied for a study performed for the Commission of the European Community (DGXII) using the energy-flow optimization model EFOM12c.[3,4] The main tasks of this project done by a European network of experts was the analysis of existing legal strategies of the EC member countries dealing with emission control, the identification of least-cost measures, cost-effective ranking of the measures, and comparison of national and EC policy to corresponding cost-effective strategies. During this study, the EFOM12c model was extended by introducing environmental subsystems in order to include emission-control options. The main focus of the analysis were SO_2 and NO_x scrubbing methods (end-of-pipe technologies), as well as low-sulfur fuels and primary measures for NO_x reduction. Furthermore, structural changes due to emission- reduction targets were important outcomes of the study.

Different scenarios were constructed to fulfill the specified tasks. The "Do-Nothing" case (keeping environmental standards and requirements on the level of 1980) was used as a baseline scenario to evaluate the effects of the other scenarios. The "Legal" case includes all those national measures related to the environment which, up to the beginning of 1987, have come into force. For the FRG the "Großfeuerungsanlagenverordnung" (Statutory Ordinance on Large Scale Combustion Installations) and the "TA- Luft" (Technical Guideline for Air Quality Control) were taken into account as well as the standards for the sulfur contents of fuels. In addition, so-called cost-efficient scenarios were created to identify the set of measures curbing the emissions of SO_2 and/or NO_x at least cost. For the comparison of the "Legal" scenario and a portfolio of cost-effective measures, the "Legal-efficient" case was used to analyze the effectiveness of measures incorporated in the "Legal" case.

The energy-demand and price projections and other key assumptions were taken from DGXII's long term energy projection ("Energy 2010" study). The following figure presents the emission projections related to the "Do-Nothing" and "Legal" cases. Only the NO_x emissions in the "Do-Nothing" case increase with time. Between 1980 and 1990 a drastic cut of nearly one half of the SO_2 emissions was achieved, although there was significant economic growth. The reasons for this were the reduction of the sulfur contents of fossil fuels and the penetration of natural gas (NG) and nuclear power generation. But current environmental policies as modeled in the "Legal" case still leave these emissions at a high level of around 10 Mtons until the year 2010. Hence, further reduction efforts might be necessary to remove environmental stresses.

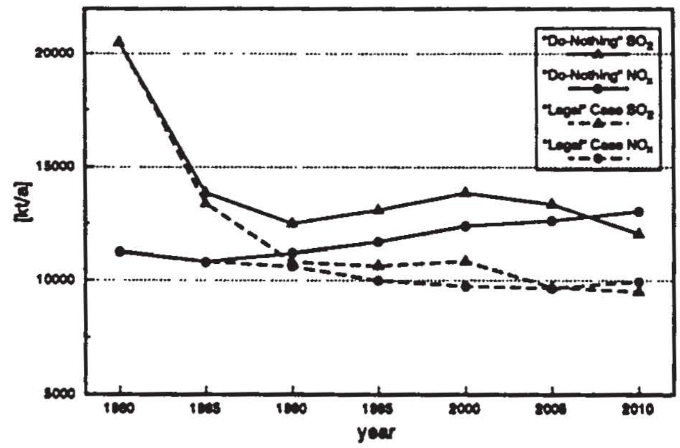

Fig. 2. SO_2 and NO_x emissions projections for the EC.

An important target of this study for international negotiations on long-range pollutant transport and definition of national emission reduction targets was the construction of national cost curves. For each of the 12 EC countries national cost curves for the reduction of SO_2, NO_x and the simultaneous reduction of both pollutants were constructed showing great differences in emission control cost on a national level. This is illustrated by the cost curves for the FRG and Greece (see Fig. 3). Generally, the reduction of NO_x is much more expensive than that of SO_2, and more ambitious goals for NO_x cannot be achieved due to a lack of efficient control measures for diesel driven engines.

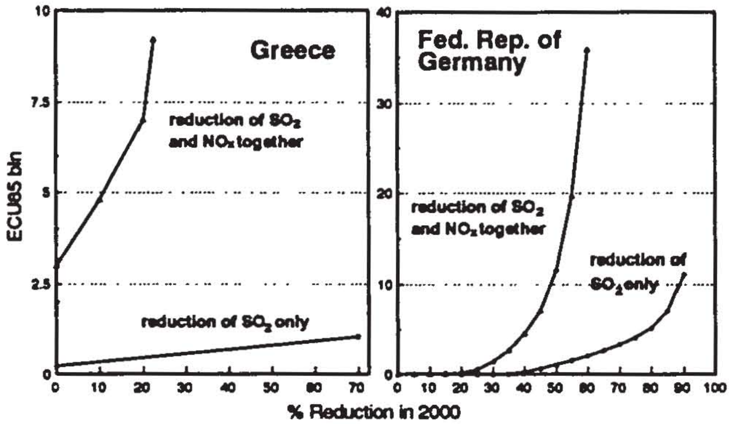

Fig. 3. National cost functions for SO_2 and NO_x reductions for Greece and the FRG.

The aggregation of all national cost functions to a European Community cost curve shows similar characteristics (see Fig. 4). The targets which may be reached nationally, as well as the related costs, depend to a high degree on the structure of the energy system and on future demand projections. For some countries (e.g. Greece), stabilization of emissions would require costs. NO_x reductions beyond the 40% margin for the EC can also be difficult to achieve with current technological options.

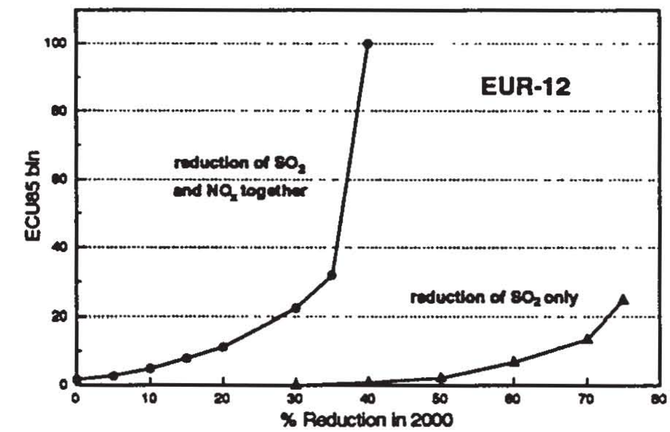

Fig. 4. EC cost functions for SO_2 and NO_x reductions.

Some national teams did not include all options available for the transport sector (e.g. controlled catalytic converters) and for some emissions (e.g. from diesel engines) no control technologies exist. For SO_2 the situation is different. Fuel switching to low-sulfur fuels and natural gas, as well as the scrubbing of SO_2 from the exhaust gases, are options that can significantly reduce these emissions for large power plants and also in the tertiary and domestic sector. The cost increases for up to 75% reduction are not as drastic as for NO_x. These cost functions correspond to a portfolio of measures which is illustrated for the FRG in Fig. 5. The set of measures is dominated by the NO_x cost-reduction measures. Fuel switching (e.g. from coal to NG) as well as technology substitution (e.g. from conventional coal power plants to IGCC) reduce both emissions and receive a credit for pollutant reductions.

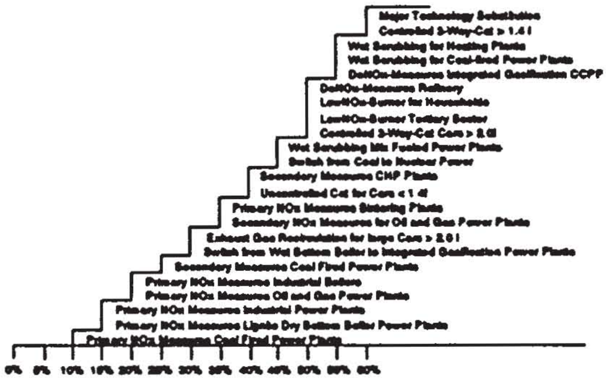

Fig. 5. List of cost-effective measures for the FRG.

A comparison between the current German policy of emission standards and a cost-effective policy showed that possible cost-savings may be significant. For the FRG, these were evaluated to be around 50% of the total discounted cost, as is depicted in Fig. 6. This result can be reached by intersectoral as well as intrasectoral switches between control measures. Structural changes (fuel and technology substitutions, enhancement of technological progress) are special measures which are cost-effective but not supported by a policy of emission standards.

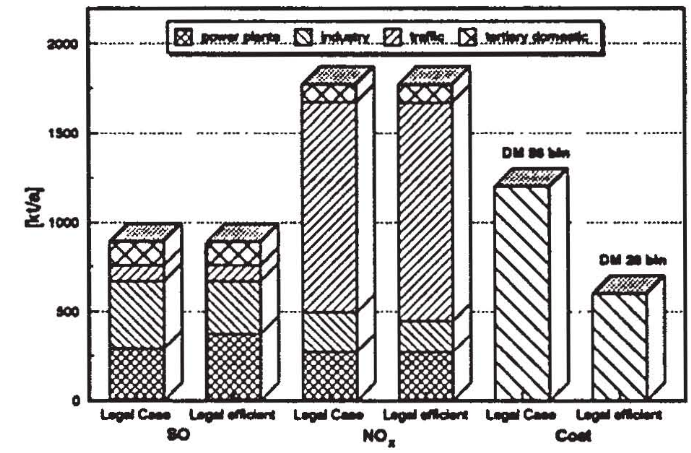

Fig. 6. Comparison of "legal" and "cost-efficient" strategies.

Our study has verified the feasibility of a model-based cost-effectiveness analysis of pollu-tant-control options. The outcome of model results may be helpful for the design of a national control policy satisfying environmental requirements at least cost and thus not wasting scarce economic resources.

5. CO_2 CONTROL STRATEGIES

Although there are still many uncertainties with regard to the timing, magnitude and regional patterns of climate change and its potential impacts, it is now generally believed that the understanding of the greenhouse question is sufficiently developed so that policy-makers should begin active collaboration to explore the effectiveness of alternative policies and adjustments. With CO_2 believed to be responsible for approximately half of the man-made greenhouse effect, the energy sector plays an important role in strategies to delay climate change. We will first illustrate the dimension of the climate issue as far as the energy sector is concerned. As already mentioned, national CO_2 emission targets that comply with global-reduction goals do not exist. But the following simple calculation provides an indication of what may be required of the industrialized nations in international negotiations on climate mitigation.

Achieving the Toronto Conference 20% reduction target requires a reduction of current global energy-related CO_2 emissions from about 20 to 16 billion tons per year. With an increase of global population to 6.5 billion people by 2005, the average CO_2 emissions per capita must then drop to 2.5 t CO_2/a. Twelve t of CO_2 per capita are now emitted in the FRG, 10 in Belgium and about 8 in France. Assuming equal emission rights for all people on planet Earth, industrialized countries such as the EC should cut their CO_2 emissions by 70 to 80% within the next 15 years. In the long run, a reduction of 90% or more would be required. Without discussing the feasibility of achieving such targets, this simple calculation illustrates the dimensions and time horizon of the necessary restructuring of our fossil-fuel-based energy system to limit climate change.

A policy to limit climate change to a tolerable level must be supported by all countries. This program requires a fair sharing of the burden and, especially from the point of view of the LDCs, a level of effort and costs that does not preclude the realization of other economic development goals. This is one reason why cost-effective measures are of extraordinary importance. The available measures for reducing greenhouse-gas emissions from the energy system fall into one of the following categories: (i) efficiency improvements and conservation in energy supply, conversion, and end use; (ii) substitution for C-rich fossil fuels (coals) by fossil fuels with lower CO_2 emissions, e.g. NG; (iii) fossil-fuel substitution by CO_2 free sources, such as renewables and nuclear energy; (iv) reduction of CO_2 at the source by removal and disposal; (v) behavioral and structural changes, e.g. modal shifts of transportation systems. The available measures for reducing CO_2 vary widely with regard to reductions of emissions, costs and availability. Some are available now or in the short-term while others need further development.

There is no doubt that there remain large potentials for energy conservation and efficiency improvements that can be implemented on an economical basis. The combustion of coal yields 1.8-2.0 times more CO_2 emissions than NG per unit of available energy. Substitution for coal of NG will therefore contribute to lowering CO_2 emissions. Substantial reserves of NG have been discovered in the world. In the future, augmented NG use should not encounter any market-penetration difficulties since the industry is now fully mature. The increase of NG use will, however, raise the danger of price increases by the producers.

Nuclear energy, which was considered to be the major contender for new energy systems in the seventies, has suffered a steadily-deteriorating image. Doing away with nuclear energy has become a critical question which has taken a new dimension because coal is no longer an attractive alternative. A great deal of the technical reduction potential for CO_2 by using nuclear energy remains untapped.

The technical development of renewable energy technologies has made important progress during the past two decades. A set of technologies has reached technical maturity and economic competitiveness, at least in some markets. But, most large-scale applications are generally not yet competitive with conventional energy sources.

Elimination of CO_2 at the source seems to be technically feasible, but there are open questions concerning the environmental impacts of the disposal of huge amounts of CO_2 into the deep oceans and costs for disposal in depleted gas or oil wells.

Table 2 provides an overview of the technical potential, as well as of the specific reduction costs of some technology options for limiting emissions of CO_2. Reduction costs, given in DM per ton CO_2 not released, span a wide range.

Negative values indicate that these measures may even have some cost advantage over the CO_2-emitting reference technology. The wide range of the unit CO_2-reduction costs is an indication that a proper selection of CO_2-reduction measures could minimize the overall costs of controlling CO_2 emissions. Available results of cost-effectiveness analysis for the Federal Republic of Germany indicate that technically feasible and cost-effective opportunities exist to allow significant CO_2 reductions without additional costs.

Table 2. Technical potentials and costs of CO_2 control measures for the FRG. Numbers refer to the FRG without the former GDR. Because of overlapping, numbers cannot be added.

Measure	Technical Potential of CO_2-Reduction	Specific CO_2-Reduction Costs
	10^6t CO_2	DM/t CO_2
Insulation of Buildings		
Swedish Standard	40	0 - 90
Low-Energy-House	80 - 110	220
Power Generation		
Improving Fossil Power Plant Efficiency (Combined Cycle)	30	(-155) - 290
Switch from Coal to NG	100	11 - 23
Switch from Coal to Nuclear Power	100 - 150	(-15) - (-3)
Renewable Energy		
Hydro Power	5	(-50) - 95
Wind Electricity	25	42 - 150
Photovoltaic Electricity	17 - 60	220 - 290
Solar Water Heating	14 - 27	(-90) - 860
Ethanol from Biomass	5 - 8	420 - 800.

A study on CO_2-control options carried out for the Commission of the European Community came up with a preliminary cost function given in Fig. 7.[5] According to the findings of this study, a reduction of the CO_2-emissions in the year 2005 relative to the 1988 emissions of the order of magnitude of 25% may be reached without additional costs.

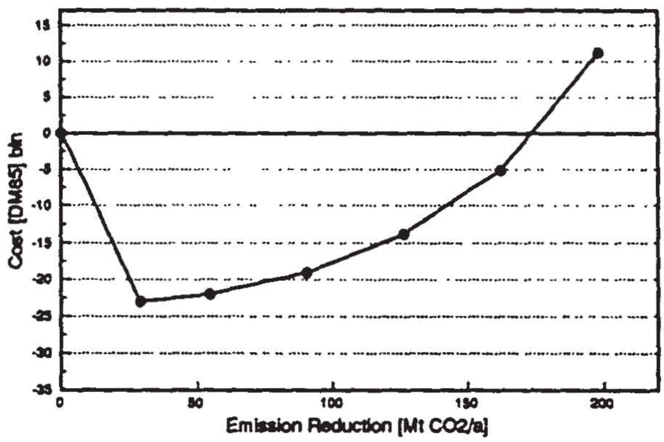

Fig. 7. CO_2 reduction in 2005 vs cost for the FRG (EFOM results).

Similar results were obtained in an analysis performed for the German Parliament.[6] Three alternative CO_2-control strategies to reduce energy-related CO_2 emissions in the year 2005 to about 70% of the current level were investigated. In the first strategy, the major emphasis was on energy conservation, the second strategy assumed a phase-out of nuclear energy by 2005 and involved greater reliance on conservation and greater contributions from renewable sources, while the third strategy had a portofolio of measures based on least-cost criteria. Figure 8 shows a comparison of the different strategies. The single most important difference between the three strategies results from their control costs. The nuclear phase-out strategy bears the highest cost. Compared with the cost-efficient strategy, the annual cost difference is of the order of 15 billion DM/a. The negative cost figure assigned to the cost-efficient strategy indicates that relative to the trend or business-as-usual scenario, a 30% reduction of CO_2 emissions could be reached without extra cost for CO_2 control.

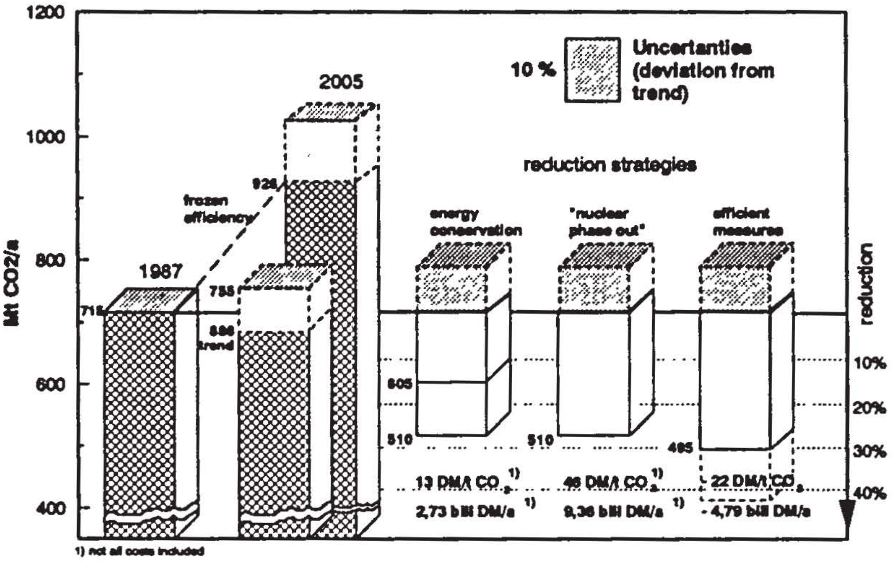

Fig. 8. CO_2 control strategies for the FRG.

Figure 9 presents the set of measures belonging to the least-cost strategy and identifies their importance. The most significant contribution to an efficient CO_2-control strategy is seen to be provided by energy conservation, followed by increased production of nuclear electricity.

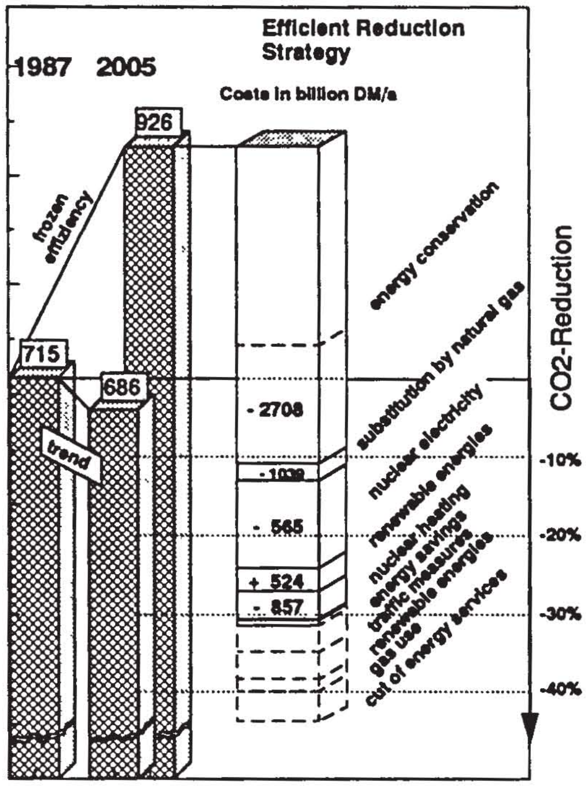

Fig. 9. Contribution of options to cost-effective CO_2 reduction strategies for the FRG.

6. CONCLUDING REMARKS

The threat of global climate change and the damage caused by air pollution is a challenge to those who determine energy and environmental policy. Adaptive as well as preventive strategies appear to be costly and require additional quantities of scarce economic resources. Maximizing the emission reduction is a prudent strategy, inspite of existing information gaps. CEA is useful in the design of an efficient and robust emission-control policy. Existing experience is promising, although improvements and extensions of the analytical approach is necessary. Amongst others, this includes an integrated analysis of the various greenhouse gases and air pollutants, a consideration of the impacts of emission control strategies on the economy, and an evaluation of the impacts of emission control strategies on world trade and prices of internationally traded energy carriers.

The compilation of national CEA results on emission control strategies generated within a common framework of assumptions could also provide useful information about a fair and equitable sharing of the burden of air pollution and greenhouse gas-emission control among countries, thereby contributing important information to the extraordinarily complex negotiations for international agreements to reduce air pollution and limit climate change.

REFERENCES

1. Commission of the European Communities, Directorate-General for Energy (DGXVII) Energy in Europe - Energy for a New Century: The European Perspective Office for Official Publications of the European Communities, Luxembourg (1990).
2. G. Schmid and A. Voß, "Cost-effectiveness Analysis: The Key for the Identification of Efficient Response Strategies to the Climate Issue; Conceptual Approach and Modelling Tools," in "Energy Technologies for Reducing Emissions of Greenhouse Gases, Proceedings of an Experts' Seminar," Vol.2, pp. 69-82, Paris (12-14 April 1989).
3. JOULE PROGRAMME, Models for Energy and Environment Subprogramme,Methodology for the Assessment of Acid Air Pollution in Europe, edited by DTP Services, Brussels, Belgium (June 1990).
4. O. Rentz, H.-D. Haasis, A. Voß, M. Meyer, and G. Schmid, "Energy and Environment: Optimal Control Strategies for Reducing Emissions from Energy Conversion and Energy Use," paper presented at the International Conference on Energy and Environmental Modelling at RISO, Denmark, and included in the conference proceedings (1989).
5. G. Schmid, "Cost-Effectiveness Analysis of CO_2-Control Strategies: The Case of the Federal Republic of Germany," Report for DGXII's CO_2 Study, Stuttgart (1990).
6. A. Voß, "Energy and Climate: Is a Climate-Benign Energy System Achievable - The Case of the Federal Republic of Germany," Paper presented at the Symposium "Energy, Environment and Climate - A Growing Challenge for a Common European House," and included in the conference proceedings, Stuttgart (1990).