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Opening Remarks

Presented by

Peter E. de Jánosi

Director, International Institute for Applied Systems Analysis

Opening Remarks

Peter E. de Jánosi

It is a great pleasure and honor to be here in Tokyo, and to have an opportunity to make a few opening remarks at a session at which so many distinguished friends and supporters are present. I would like to single out three by name: Professors Kondo and Mukaibo, who have been key figures in IIASA's relationship with Japan, and Professor de Souza, who is one of our generous hosts. I gratefully acknowledge all the spiritual and financial support they and all of you have given to make this one-and-a-half-day Symposium possible. It is truly heartwarming to see so many important individuals and institutions in Japan involved and providing so much attention and care. There simply have been too many of you working on our behalf to mention individually as my time is limited. I apologize for my inability to do so, but I cannot refrain from mentioning the major groups involved, namely, the Japan Committee for IIASA, the Special Committee for the IIASA Days in Japan, the UN University, and the sponsors and supporters of these days: MITI/NEDO, the Environment Agency, the Global Environmental Forum, and CRIEPI. IIASA deeply appreciates your help and devotion.

Allow me to say a few words about IIASA, generally, and about the special characteristics the Institute has acquired over its 24-year existence.

IIASA is only one, albeit a very special, example of an international, interdisciplinary research enterprise. It is an example of a relatively new and rare species. It is curious that while most scientists and disciplines have had an international outlook for many years, international research institutions have not been in existence for long. Individual mathematicians from all parts of the globe have kept up with one another's work, as have chemists, physicists, and economists. But how many internationally sponsored institutions can we think of that facilitate the work of these disciplines, let alone foster their collaboration?

Of course, if one visits some of the major national research centers, one often finds a strong presence of scientists from different countries. This is true for Princeton University, institutes of the Max Planck Society, or Oxford University, to mention only three. But these are national institutions, sponsored and supported primarily by national resources.

One can also point to already well-developed activities that have international dimensions based on bilateral cooperation between two countries. It has indeed become a widespread practice for two countries to agree to an exchange of scientists or to collaborate on specific topics.

Fortunately, one can also find a growing number of international research networks and collaborations. The laudable efforts of the International Geosphere-Biosphere Program (IGBP) and the Human Dimensions Program (HDP) should clearly be recognized in this context, as should the important research work for the Intergovernmental Panel on Climate Change (IPCC).

Some of the world's best scientists have been and are enlisted to give attention to a set of selected problems on which they work together with junior colleagues. Most of the studies are carried out by the researchers at their home institutions, with occasional workshops and other types of gatherings of the collaborators. After completion of the work, the collaboration ceases.

Of course, all of the above elements are important and praiseworthy, and meet very important objectives. It is hoped that they will continue to expand and flourish. But they are not what I am referring to when I say that international, interdisciplinary research enterprises are a relatively rare breed. What I am referring to is an international research *institution*, that is, an organization with an established base; a set of interests, values, and practices; an ability to give sustained attention to problems; and a presence that goes beyond the immediate specific activities in which the institution is engaged. Institutions of this sort can cultivate international, interdisciplinary research in an innovative fashion not only on existing but also on emerging problems.

Why are there so few such institutions? Certainly it is not because there is a lack of world problems that transcend national borders. Rather, I suspect the reasons are that the establishment of international institutions requires not only scientific, but also political leadership, and a long-term commitment. Moreover, if the institution is sponsored on a multinational basis, each sponsor must give up some control as the institution must respond to many different needs, not just to those of a single country (or two, in the case of bilateral collaboration).

Despite the rarity of the species, of which IIASA is one, there seems to me to be great value in their existence. Perhaps there is no better way to prove this point than to have you participate in this Symposium and to show you what we are doing.

Many of the 15 research projects IIASA sponsors have a direct bearing on Agenda 21 and on global change and sustainability, with particular attention to human dimensions. IIASA interprets its mission broadly as we see global change and sustainability encompassing not only environmental issues, but also economic, technological, demographic, and energy topics, to name just a few.

The projects have been chosen with much care and attention on the basis of a variety of considerations, and they are, in many cases, guided by distinguished international scientific advisory committees. Every three years groups of projects also benefit from evaluations by an international panel of outstanding scientists appointed by IIASA's Governing Council.

The strong emphasis on openness and quality is one of the hallmarks of IIASA's work in the 1990s. We face a highly competitive world in which scarce resources are allocated to us only if we can show that what we are doing is valuable and relevant.

Most of the projects we choose tend to deal with topics that concern policy makers. The selection of our work therefore is dictated not by science alone but also by societal needs, and it is for this reason that Agenda 21 is of great importance to us. At the same time, we do want to bring the best that science has to offer into all of our analyses.

Modern society has become an intricate net of highly complex systems, and to understand these systems we must increasingly rely on capabilities deriving from a broad spectrum of knowledge. An interdisciplinary approach is the only way to begin to comprehend the significance of these complex systems and then to seek solutions. Most of IIASA's projects, therefore, have a strong interdisciplinary character.

Our projects are organized around three major, interrelated themes: Global Environmental Change, Global Economic and Technological Transitions, and Systems Methods for the Analysis of Global Problems. A number of projects representative of our work will be described during this Symposium. The presentations will illustrate not only what topics receive attention, but also our analytical approaches and the way the Institute is organized. It is important to note that IIASA is an institution with a resident staff of about 140 researchers and professionals from 27 countries, and a collaborating network of a somewhat larger size. We also have a group of important alumni, numbering around 2,100.

Because of this in-house research capacity, IIASA and its staff are in a particularly good position to make sustained and useful contributions to many other international efforts. These include not only our distinguished host, the UN University, but also other UN agencies, the World Energy Council, the IPCC, IGBP, and HDP.

Unfortunately, the Symposium is too short to enable us to present some of the work of the other seven projects that are not on the Tokyo program. Thus, for example, we will not have an opportunity to present the fine work on water quality management in Central and Eastern Europe that builds on many years of IIASA research on water quality. Nor can we talk about a major study on Forest Resources, Environment, and Socio-Development of Siberia; this study has developed the first inventory of forest wealth in that region, and is now conducting integrated analyses of forest management, forest ecology, and greenhouse gases and the carbon cycle. Another project of special interest to Central and Eastern Europe and Russia deals with the dramatic economic transitions. And IIASA's extensive methodological work goes well beyond the one project you will hear about.

What are the general distinguishing characteristics of IIASA? I have already mentioned some of these, but let me summarize the most important:

- An outstanding international sponsorship from 17 science academies or committees in as many countries.
- A nongovernmental foundation, which provides independence and neutrality, although supported by governments.
- An international, interdisciplinary approach that aims to conduct policy-oriented, high-quality, scientific work.
- Emphasis on quality control through peer review.
- Proven institutional capacities that include the mobilization of first-class researchers, a large network of collaborators, the establishment of resident research teams, and convening power.
- A concern with training future generations of internationally oriented, interdisciplinary researchers.
- The pursuit of a broad mandate in a flexible, responsive, and unbureaucratic fashion.

I hope I have conveyed to you some of the major features and goals of IIASA. I also hope I have provided the basis for the detailed presentations of my colleagues.

In conclusion, I would like to stress the importance of the Japanese scientific and policy communities, as their contributions to IIASA have been so numerous. Japan was, in fact, a founding member country of IIASA in 1972, and since then many Japanese have been at the Institute for varying periods of time. The number of Japanese alumni now stands at 86. Moreover, in the past five years we welcomed 193 conference participants and 248 visitors from Japan. The involvement of Japan in IIASA has been especially noteworthy and encouraging in recent years, and we currently have seven part- or full-time Japanese staff members, more than in any previous year.

The Institute's effectiveness in dealing with the many issues of global change and sustainability depends, to a large extent, on the commitment and effectiveness of our sponsors in each member country. In this regard, we are exceptionally fortunate to have such a fine group of outstanding representatives serving on the Japan Committee for IIASA. The support of the Committee is proof that in Japan it is fully recognized that international scientific cooperation at the end of the 20th century is not a dispensable luxury, but an absolute necessity.

Energy and Environmental Strategies for Sustainable Development

Presented by

Nebojša Nakićenović
Project Leader, Environmentally Compatible Energy Strategies

A Summary of the Joint IIASA and WEC Study on Long-Term Energy Perspectives

Arnulf Grübler,[1] *Michael Jefferson,*[2] *Nebojša Nakićenović*

Introduction

This paper summarizes a study of long-term energy prospects conducted jointly by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC). The study report, *Global Energy Perspectives to 2050 and Beyond*, was presented at the 16th WEC Congress in Tokyo, October 1995 (IIASA and WEC, 1995).

The study is based on the formulation of alternative scenarios, corroborated by an integrated assessment framework of energy-environmental models under development at IIASA (for an overview see the box on methodology). The 1993 WEC Commission report, *Energy for Tomorrow's World*, describes global energy perspectives and related issues to the year 2020 (WEC, 1993). The Commission report's extended outline to 2100 serves as the starting point for this summary.

The Cases/Scenarios

Three alternative cases of long-term economic and energy developments were used to explore alternative possible futures. The cases are labeled A (High Growth), B (Middle Course), and C (Ecologically Driven). The key features of the three cases are summarized in *Table 1*.

In the early stages of the study it became apparent that it was necessary to move beyond the formulation of three alternative cases. More possibilities opened up than originally anticipated, and the three cases blossomed into six scenarios of energy supply systems alternatives. Three variants of Case A (Scenarios A1, A2, and A3) and two variants of Case C (Scenarios C1 and C2) were developed. For the Middle Course, Case B, only one scenario was developed as it was designed to represent a future characterized by incremental and gradual changes. The three cases have several common features:

- World population grows in line with current medium projections made by the World Bank, United Nations, and IIASA to about 10 billion in 2050 and approaching 12 billion in 2100. No useful purpose is served in using high and low projection alternatives, particularly as these alternatives would divert attention from the main, energy-oriented thrust of the study. The World Bank's estimates have, therefore, been used.
- The world is divided into 11 regions (*Figure 1*), defined on the basis of geographical proximity and similarity of economic and energy systems patterns. Most of the results are reported for three "macro-regions": the transitional economies of the former Soviet Union and Central and Eastern Europe (labeled REFs); the current developing countries (DCs); and the industrialized countries of the Organisation for Economic Co-operation and Development (OECD).

[1] International Institute for Applied Systems Analysis, Laxenburg, Austria.
[2] World Energy Council, London, UK.

Methodology

Reproducibility of results adds to their validity. This is especially the case when presenting long-term scenarios for which there are no established, rigorous validity proofs. A necessary – though not sufficient – condition for reproducibility is a good description of the methods that produced the results. This appendix presents a summary description of the methods used in the study, and references where more complete descriptions can be found.

The analysis started with two principal exogenous variables: population growth by region and per capita economic growth by region. Levels of primary and final energy consumption were derived using a model developed at IIASA labeled *Scenario Generator* (SG) (Gritsevskii, 1995). It is essentially a combination of an extensive data base of historical data on national economies, and their energy systems, and empirically estimated equations of past economic and energy developments.

For each scenario, the SG generated plausible future paths of energy use consistent with historical data and with the specific features that were specified for the scenarios, e.g., high or moderate economic growth, rapid or gradual energy intensity improvements, technological development across the board or rapid development in green technologies and slow development for fossil fuels.

Two other models were then used in an iterative mode for testing the consistency among all the parts of each scenario. A model of energy-economy interactions, called 11R, was used to check for consistency between a region's macroeconomic development and its energy use. The 11R model is a modified version of Global 2100, originally published in 1992 (Manne and Richels, 1992), and subsequently used widely in energy studies throughout the world. IIASA's energy supply model, called MESSAGE III, provided detailed estimates of energy demand and supply (Messner and Strubegger, 1994, 1995). MESSAGE III is a dynamic linear optimization model, calculating cost-minimal supply structures under the constraints of resource availability, the menu of given technologies, and the demand for useful energy. Both models use a discount rate of 5% per annum. The two models are used in tandem because they correspond to the two different perspectives from which energy modeling is usually done: top down (11R) and bottom up (MESSAGE III). The model-linking methodology is described in Wene (1995).

The regional acidification impacts were calculated using IIASA's RAINS model (Alcamo *et al.*, 1990, 1995). It is a modular simulation model with sections to calculate emissions from given levels of activity in the energy sector and energy end uses, subsequent atmospheric transport and chemical transformations of those emissions, deposition, and ecological impacts. The last calculations are based on a spatial resolution of a 150-km grid.

The impacts of energy biomass production on land use and potential conflicts with food production were calculated using IIASA's Basic Linked System (BLS) of national agricultural models (Fischer *et al.*, 1988, 1994). BLS consists of sectorially disaggregated macroeconomic models with detailed agricultural production functions that take into account all major inputs (land, fertilizer, capital, and labor) required for the production of 11 agricultural commodities.

- Social and economic development is substantial, particularly in the Southern Hemisphere. In the next century, the current distinction between "developing" and "developed" countries will become inappropriate as affluence increases throughout the world.
- Energy efficiency improvements steadily increase, but remain in line with historic experience. Evidence of the past decade suggests modest expectations are justified until proved otherwise.
- The quantity and quality of energy services grow steadily as the drive for cleaner and more convenient fuels continues.
- Formal top-down and bottom-up models have been used to check for internal consistency of the scenarios.

In the following three sections we summarize the differences between the cases and their scenarios. Each scenario covers the energy system as a whole from resource extraction to the provision of energy services. They are not simply energy supply or energy demand scenarios.

Table 1: Summary of three energy development cases in 2050 and 2100.

	Case A High Growth	Case B Middle Course	Case C Ecologically Driven
Population in billions			
2050	10.1	10.1	10.1
2100	11.7	11.7	11.7
GWP[a] in trillion US dollars			
2050	100	75	75
2100	300	200	220
Energy intensity decline	medium	low	high
PE/GDP,[b] %/yr			
World (1990–2050)	–1.0	–0.7	–1.4
World (1990–2100)	–1.0	–0.8	–1.5
Primary energy demand, Gtoe[c]			
2050	25	20	14
2100	45	35	21
Resource availability			
Fossil	high	medium	low
Nonfossil	high	medium	high
Technology costs			
Fossil	low	medium	high
Nonfossil	low	medium	low
Technology dynamics			
Fossil	high	medium	medium
Nonfossil	high	medium	high
CO_2 emission constraint	no	no	yes
Carbon emissions, GtC[d]			
2050	9–15	10	5
2100	7–22	14	2
Environmental taxes	no	no	yes
Number of scenarios	3	1	2

[a]Gross world product.
[b]Primary energy/gross domestic product.
[c]Gigatonnes oil equivalent.
[d]Gigatonnes of carbon.

Case A: High Growth

Case A assumes high rates of economic growth and technological progress, a liberal international trading regime, and preference for markets over detailed regulation. Economic growth is some 2% per annum in OECD countries, and double that figure in developing countries. This relatively high growth facilitates rapid turnover of capital stock and shifts in economic structures which promote efficiency improvements and technological advance. Toward the end of the 21st century, average global per capita income in Case A would surpass the highest national levels observed today, indicating that current categories of "developed" and "developing" regions will become obsolete.

As indicated, Case A is three-pronged with respect to possible alternative energy systems developments:

- *A1*, labeled "clean fossils," favors neither coal nor nuclear, but as a result of technological change sees the tapping of the vast potential of conventional and unconventional oil and gas resources.

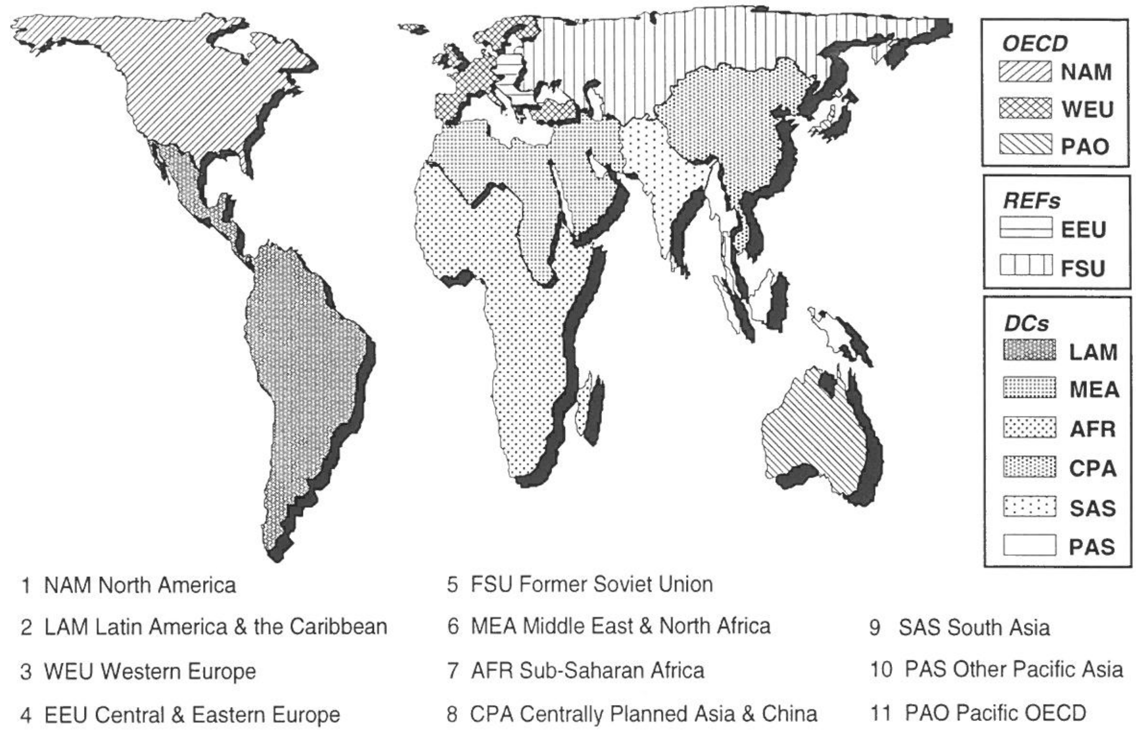

Figure 1: The 11 world regions in the IIASA and WEC study.

Consequently, fossil fuel resources are sufficient to allow a smooth transition to alternative supply sources based on acceptable nuclear power and new renewables, matched with high-quality energy carriers in the form of electricity, liquids, gas, and – later – hydrogen. Coal is regarded as a relatively unattractive "backstop" fossil fuel and continuously loses market share.

- *A2* is labeled "dirty fossils." For a variety of reasons concerns about potential climate change wither away, and coal's vast resources make it the fossil fuel of choice as conventional oil and gas resources dwindle. Local and regional sulfur and nitrogen emissions are controlled through add-on technologies; however, challenges continue as coal is exploited at ever deeper and more remote locations, and conversion to synliquids is increasingly required.
- *A3* is labeled "bio-nuc." Large-scale renewables and a new generation of nuclear power lead to a technology-driven transition to a post-fossil fuel age. The transition parallels that which occurred when industrialized countries moved from fuelwood through coal to oil and natural gas. In this scenario, natural gas is the transitional fossil fuel of choice, supported by economically competitive oil resources. There is little pressure to exploit nonconventional oil resources or large volumes of coal. By 2100 there is almost equal reliance on nuclear energy, natural gas, modern biomass, and a fourth category composed mostly of solar energy with small contributions from wind, geothermal, and a few ocean/tidal schemes.

Case B: Middle Course

Case B is a single scenario, with more modest assumptions about economic growth, technological development, removal of trade barriers, and development aspirations of the South than Case A. Recent setbacks and slower economic restructuring than anticipated in the transitional economies, together with weak economic performance in countries in sub-Saharan Africa and some other developing countries, are also reflected in the comparatively modest near-term economic growth assumptions of Case B.

This case has the greatest reliance on fossil fuels of any scenario except the coal-intensive Scenario A2. Beyond 2020 the failure to match depleting fossil fuel resources with the necessary technological advances and exploration and production effort creates challenges for energy supply structures. There is pressure to move into costlier categories of unconventional resources and more remote conventional resources of fossil fuels; financial and environmental constraints loom increasingly large.

This scenario may be the easiest to achieve or a case of muddling through.

Case C: Ecologically Driven

Case C is the most ambitious by being highly optimistic about the development of technology diffusion and geopolitical innovations to meet the challenges of the environment and international equity. Substantial resource transfers, from North to South, recycle environmental taxes to spur growth in the South, enabling wide participation in international environmental agreements and policies to reduce emissions from energy supply and end use. Globally, economic growth falls short of Case A but slightly surpasses that of Case B, allowing a substantial reduction in economic disparities.

Case C incorporates policies which reduce carbon emissions to 2 GtC (gigatonnes of carbon) by the end of the 21st century. These can be achieved either through economic instruments or through effective command and control measures. Model checks confirm that the latter could create inefficiencies. It is believed that incentives rather than taxes – carrots rather than sticks – are more likely to get organizations and individuals to respond positively and quickly.

In Case C nuclear energy is at a crossroads illustrated by two scenarios. Scenario C1 assumes nuclear is a transient technology that is phased out entirely in the long term, leaving new renewable forms of energy to substitute for fossil fuels. Scenario C2 assumes a new generation of small-scale (200 to 400 MW) nuclear reactors is developed which is, and is also perceived to be, inherently safe.

Key Underlying Elements

This paper cannot reproduce the details contained in the full study (IIASA and WEC, 1995), but five salient elements are summarized here: population prospects, economic growth, energy intensity, technological advance, and the energy resource base. To the industrialization process, which continues in many countries, have been added four structural transformations: urbanization, the transition from noncommercial to commercial forms of energy, increasingly convenient, clean, and flexible forms of energy (essentially increased quality), and decreasing energy intensity (specific energy needs per unit of economic activity decline with economic development).

These transformations began in the most developed parts of the world, and have spread globally; however, significant differences remain between regions. Such structural shifts are generally least advanced in developing countries where population is expected to grow rapidly.

Population Prospects

One medium projection of the world's population was assumed in the study, and is illustrated in *Figure 2* (Bos *et al.*, 1992). World population is expected to double in 70 years from 5 billion in 1990 to 10.6 billion in 2060. The most recent doubling occurred over approximately 40 years. Therefore, population growth is slowing, but future absolute increases will be larger than ever before.

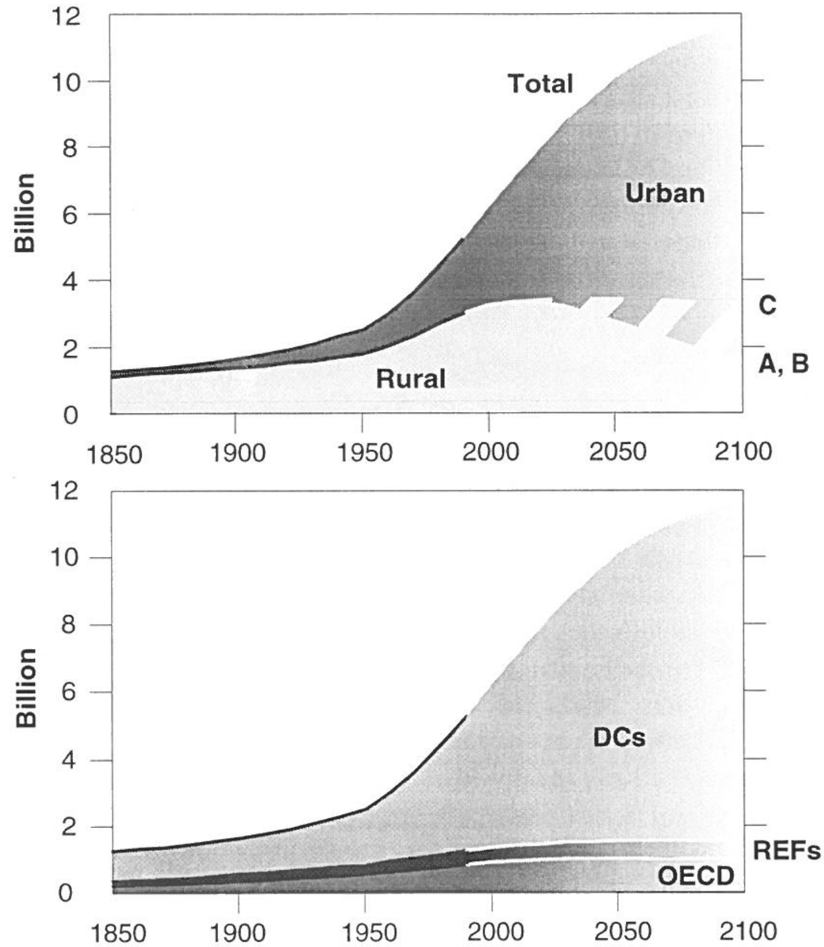

Figure 2: World population from 1850 to 1990 and World Bank projection to 2100 (Bos *et al.*, 1992), rural-urban (top) and by macro-region (bottom). Urbanization trends are based on UN (1994) and Berry (1990).

Most of this growth will occur in the current developing countries or the South. Not only will the energy consumption balance shift from North to South; the geopolitical balance may also shift in this direction.

The rate of urbanization will be even faster than the rate of overall population growth. Most of the largest cities will be in the South. Today, highly urbanized populations have relatively high per capita energy consumption levels (they also have relatively high income levels). In the Ecologically Driven Case C urbanization is assumed to proceed at a somewhat slower rate than in the other two cases because locally appropriate, small-scale new renewable sources of energy become available to rural communities and slow the urbanization process.

Economic Growth

The economic growth assumptions to 2050, by case and by region, are given in *Table 2*, placed in their historical context since 1850. Experience shows both an uneven process across countries and over time, and a certain degree of convergence as less developed economies catch up with more developed ones. As a result, the scenarios assume that all countries and regions eventually achieve a *takeoff*

Table 2: Economic growth rates, historical and 1990 to 2050 (%/yr).

	Historical			Case					
	mer		ppp	1990–2020			2020–2050		
Region	Since 1850	Since 1950	Since 1950	A	B	C	A	B	C
NAM	3.5	3.3	2.1	2.3	2.0	1.7	1.6	1.4	1.1
WEU	2.4	3.7	2.2	2.2	1.9	1.7	1.6	1.3	1.1
PAO	3.9	6.2	3.6	1.9	1.5	1.4	1.2	0.9	0.8
EEU	2.1	3.9	2.4	2.3	0.9	1.3	4.6	3.6	3.2
FSU	3.5	5.2	3.5	1.2	0.7	1.1	5.4	3.8	3.3
CPA	2.9	6.1	4.3	7.2	5.0	6.7	4.4	4.0	4.0
SAS	2.0	4.5	3.1	3.9	3.6	3.7	4.6	3.5	4.3
PAS	n.a.	9.8	6.8	5.7	4.4	5.3	3.3	3.1	3.1
MEA	n.a.	4.6	3.1	3.6	3.3	3.2	3.9	3.0	3.0
AFR	n.a.	2.7	2.0	3.3	3.0	3.1	4.7	3.5	3.9
LAM	3.7	4.2	2.9	3.1	3.0	2.8	3.2	2.8	2.6
World	n.a	2.9	2.0	2.7	2.2	2.2	2.6	2.0	2.1

Historical Data Sources: Maddison, 1989; UN, 1993.

into accelerated economic development and industrialization, and conditional convergence in long-term levels of economic development.

The study further develops the calculation of economic growth not simply based on gross domestic product calculated at market exchange rates (GDP_{mer}), but also calculated at purchasing power parities (GDP_{ppp}). Purchasing power parities give a more accurate representation of the relative level of economic activities for economies that do not have a free market for foreign currency exchange. Furthermore, they do not assume that domestic prices (e.g., for food in developing countries) are similar to international prices. Use of GDP_{ppp} somewhat modifies the wide disparities in income, wealth, and consumption around the world. Under the GDP_{mer} measure, the richest 20% of the world's population produces and consumes 80% of the world's product; under the GDP_{ppp} measure, the richest 20% consumes *only* 60%. The distinction becomes particularly important when considering energy intensity differences among regions.

Energy Intensity

Energy intensity is a broad aggregate measure, linking energy consumption to units of economic activity. Energy intensities have tended to decline, in the USA and the UK, for instance, for some 125 to 150 years if total energy (noncommercial and commercial energy combined) is taken into account. If only commercial energy is considered, in the USA, for example, the start of the decline in energy intensity is postponed – until about 1920. *Figure 3* provides historic changes in primary energy intensity for total energy (solid lines) and commercial energy only (dotted and dashed lines) for selected countries. For developing and reforming economies, both GDP measures (at market exchange rates and at purchasing power parities) are provided. Thus India's total energy intensity declines quite sharply based on GDP_{mer}, but remains much higher than the more stable evolution at GDP_{ppp}. Commercial energy intensity, nevertheless, rises sharply on both GDP measures.

It is assumed in the study that aggregate energy intensities generally improve over time but take into account the impact of commercial energy carriers substituting for traditional energy forms and

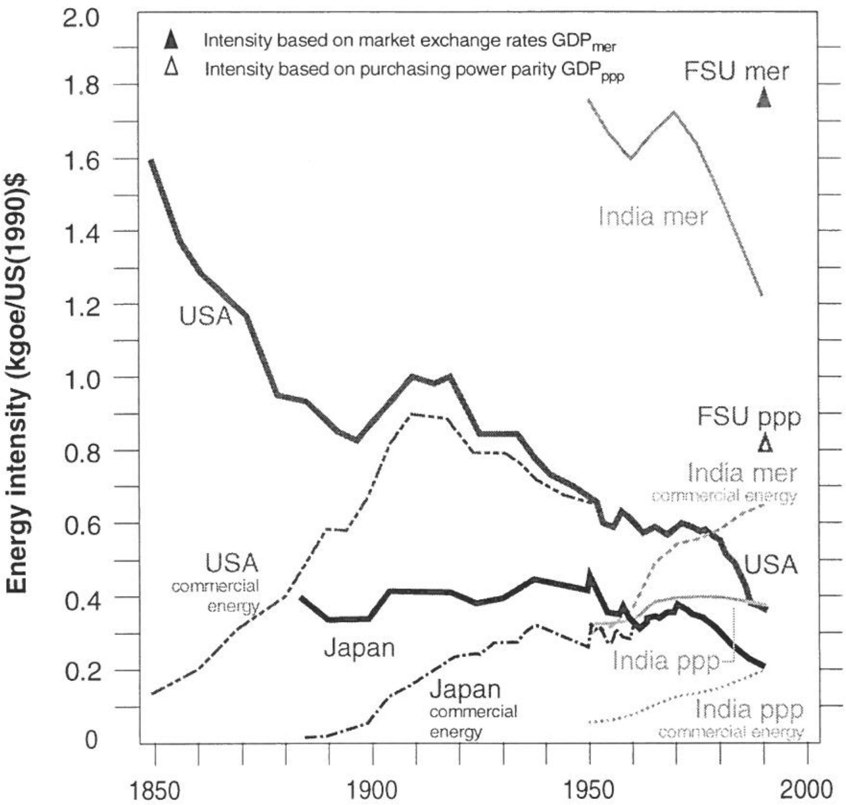

Figure 3: Primary energy intensity for selected countries, total and commercial energy in kgoe (kilograms oil equivalent) per US dollar GDP_{mer} and GDP_{ppp} at 1990 prices. Data sources: Nakićenović, 1987; Martin, 1988; and TERI, 1994.

technologies. Once this process is largely completed, commercial energy intensities decrease in line with the pattern found for aggregate energy intensities in industrialized economies. There are, of course, persistent differences between countries and these reflect a range of historical circumstances, development histories, and pricing and cultural patterns, including attitudes toward technology. Historically, energy intensity improvements tend to be path dependent, leading only to conditional convergence between countries and regions over time, a hypothesis that is also incorporated into the scenarios.

The resulting global energy intensity improvement rates are 1.0% per annum for High Growth Case A, 0.8% per annum for Middle Course Case B, and 1.4% per annum for Ecologically Driven Case C. Details are given in *Tables 3* and *4*.

In comparing the energy intensity improvement rates presented in this paper with other studies and earlier WEC cases, important definitions and measurement issues must be kept in mind. The measurement issues are illustrated later in the paper for Middle Course Case B for three of our eleven world regions, giving energy intensity improvement rates (percent per year) to 2020 for total primary energy (TPE) and commercial primary energy (CPE) and for market exchange rate (GDP_{mer}) and purchasing power (GDP_{ppp}), respectively.

The dynamics of energy intensity improvements change drastically for developing regions as exemplified by Centrally Planned Asia and China and sub-Saharan Africa. The generally higher energy intensity improvements for Centrally Planned Asia and China are the result of the much higher short-term economic growth rates for Centrally Planned Asia and China than for sub-Saharan Africa; higher GDP growth leading to faster turnover of capital stock yields faster energy intensity improvements in the

Table 3: Three scenarios of energy intensity improvements (primary energy per GDP_{mer}, %/yr).

	Case A	Case B	Case C	Case B1 – C[a]	
	1990–2050	1990–2050	1990–2050	1990–2020	
OECD	–1.2	–1.1	–2.0	–1.9	–2.8[a]
REFs	–2.1	–1.7	–2.2	–1.2	–2.7[a]
DCs	–1.6	–1.2	–1.9	–0.8	–2.1[a]
World	–1.0	–0.8	–1.4	–1.3	–2.4[a]

[a]Range of WEC Commission's report (WEC, 1993). Improvement rates are not directly comparable as based on purchasing power parity (ppp). It should be emphasized that the WEC Commission specifically rejected adoption of any business-as-usual cases, and noted that in recent years groups of industrialized countries have achieved overall energy intensity reductions exceeding 1.5% per year (e.g., the European Union since 1974) and exceeding 2.5% per year if road transportation is excluded. But the achievements made by a few countries over a short period may be difficult to duplicate by many countries over a long period.

Table 4: Energy intensity improvements 1990–2020 for three regions (%/yr).

Region	TPE/GDP_{mer}	TPE/GDP_{ppp}	CPE/GDP_{mer}	CPE/GDP_{ppp}
NAM	–1.2	–1.3	–1.2	–1.3
CPA	–2.2	–0.7	–1.5	0.0
SAS	–1.0	–0.3	0.2	0.8

TPE - Total primary energy.
CPE - Commercial primary energy.

scenarios. Thus, the evolution of energy intensity, when measured as energy consumption per GDP_{mer}, results in a very high improvement rate. Conversely, commercial energy intensity measured per GPD_{ppp} assume positive values, i.e., commercial energy consumption grows at least as fast as GDP_{ppp} in Case B.

Technological Advance

The full IIASA/WEC report devotes considerable space to the dynamics of technical progress and to technological innovation and diffusion drawing on IIASA's data bank of 1,400 technologies. Technological change, together with economic structural change, is an important driving force for the evolution of energy intensity.

The three cases assume different rates of technological progress and learning, and the varying impact of related features such as the relevance of international trade requirements on some technologies and the scope of local development and manufacture of others. In all cases, energy options which are not technically feasible today are excluded. Nuclear fusion, for example, is excluded. Hydrogen as an energy carrier is included, because it can be produced with current technologies though not at current commercial costs.

Case A (High Growth) considers substantial advances in energy production, conversion, and end-use technologies. These advances are demonstrated across the board: for hydrocarbon exploration and extraction; nuclear electricity generation and hydrogen; renewable sources of electricity generation and biofuel production and conversion; and advanced end-use conversion technologies such as fuel cells.

In Case B (Middle Course) the advances are less substantial than in Case A, reflecting less concerted research, development, and diffusion efforts. In Case B technological change largely focuses on incremental improvements of existing technologies.

Case C (Ecologically Driven) strongly favors low-carbon fossil and renewable energy supplies and high efficiency end-use technologies. Technologies in these sectors benefit from improvements rates

Table 5: Global fossil and nuclear energy reserves, resources, and occurrences, in Gtoe.

	Consumption		Reserves	Resources[a]	Resource base[b]	Additional occurrences
	1850–1990	1990				
Oil						
Conventional	90	3.2	150	145	295	
Unconventional	–	–	193	332	525	1,900
Natural gas						
Conventional	41	1.7	141	279	420	
Unconventional	–	–	192	258	450	400
Hydrates	–	–	–	–	–	18,700
Coal	125	2.2	606	2,794	3,400	3,000
Total[c]	256	7.0	1,282	3,808	5,090	24,000
Uranium	17	0.5	57	203	260	150
in FBRs[d]	–	–	3,390	12,150	15,550	8,900

–, negligible amounts; blanks, data not available.
[a]Resources to be discovered or developed to reserves.
[b]Resource base is the sum of reserves and resources.
[c]All totals have been rounded.
[d]Fast breeder reactors.
Source: IIASA and WEC, 1995.

equal to those in Case A. Technological developments in other energy sectors develop slowly, as in Case B.

The Energy Resource Base

The resource base used for the study includes all potentially recoverable coal, conventional oil and natural gas, unconventional oil (shale, tar sands, and heavy crudes), and unconventional natural gas (gas in Devonian shale, tight sand formations, geopressurized aquifers, and coal seams). Quantities not considered potentially recoverable are classified as "additional occurrences" and are excluded from the resource base. Hence, they are not taken into account in the cases/scenarios. The quantities in such occurrences as methane hydrates in tundra regions and in the sea and natural uranium dissolved in sea water are huge. *Table 5* provides the details, drawing upon numerous sources, which are acknowledged in the full study (IIASA and WEC, 1995).

The availability of the fossil fuel and uranium resource bases varies in the cases and scenarios. It ranges from optimistic in Case A (Scenarios A1 and A3), through cautious (Scenario A2 and Case B), to conservative (Case C). As mentioned earlier, none of the scenarios assume any "additional occurrences" are brought on stream, but they do indicate the hypothetical availability of enormous quantities.

The fossil fuel resource figures given in *Table 5* are certainly sufficient for more than 100 years, even in the highest Case A Scenarios. This is not to suggest that temporary or structural energy shortages cannot occur; simply, there are no basic geological constraints. There are likely to be other barriers to using such large quantities of fossil energy: technical, financial, and environmental. For instance, cumulative carbon emissions of the full exploitation of fossil resources would correspond to six to seven times the current atmospheric CO_2 concentration, which now approaches 360 ppmv (parts per million by volume). Local environmental impacts could also be chronic in many parts of the world (see discussion below).

In the future the use of uranium will depend in part upon the resolution of current controversies surrounding operational safety, waste disposal, and proliferation and in part on successful development of new technologies.

Renewable energy resources (with the exception of a few hydropower sites) offer much lower energy densities than fossil fuels. They are limited, therefore, not by the magnitude of their energy flows (which are huge by any standards) but by how these flows can be harnessed and converted to fuels to provide energy services. This implies not only appropriate technology and finance, but also the resolution of potential local environmental impacts.

Nevertheless, it is a fact that the earth annually intercepts about 130,000 Gtoe (gigatonnes oil equivalent) of solar energy compared with current total global energy consumption of about 9 Gtoe. This is one reason why it is not unlikely that, in the long run, the direct uses of solar energy from photovoltaics to solar thermal will account for a major part of renewable energy. A second reason is that other forms of renewable energy may have unacceptable local environmental impacts either when pursued on a large scale (plantation biomass) or when pursued in particular locations (protected landscapes, sensitive estuaries, rare natural habitats).

The key issue, therefore, is what fraction of renewable energy flows can and will be harnessed for the energy purposes of future generations. The WEC's reports, *Energy for Tomorrow's World* (WEC, 1993) and *New Renewable Energy Resources: A Guide to the Future* (WEC, 1994), identify renewable energy potentials by the year 2100 of up to 13 Gtoe, of which 10 Gtoe could be supplied by "new" renewables – modern biomass, solar, wind, geothermal, ocean/tidal, and small hydropower (under 10 megawatts).

Progress toward this long-term potential is, however, likely to be slow – particularly with current policies. Major, effective, and internationally coordinated policy support would be required if developments are to be accelerated over the next two to three decades. In the longer term, the potentials for renewables increase significantly as technological and both absolute and relative cost improvements take place.

Prospects for Energy Systems

The energy system is service driven from the bottom up, while energy flows are resource and conversion process driven from the top down. Energy flows from energy sources to end use and driving forces from population growth to technological change interact intimately. In the study, therefore, the dichotomy between supply and demand has been replaced with the broader perspective foreshadowed in the WEC's report *Energy for Tomorrow's World*:

> The energy community is the captive of its own technology in continuing to use these distinctive terms in ways which fail to recognise them as elements of ... a system which should be driven not by the exigencies of primary energy supply, trade or the energy market but by the end-point services which energy is the means of providing. [WEC, 1993, p. 246]

The scenarios are, therefore, described in terms of primary and final energy consumption. Primary energy depicts the structure of energy extraction and conversion, while final energy shows the structure of energy end use.

The six scenarios are intended to illustrate the possibilities arising from steps taken to develop new energy technologies, energy resources, and financial institutions over a time period, guided by policy and end-use objectives that permit a range of outcomes. There is also time to achieve capital turnover and fundamental change in the energy system. By 2020, many current energy end-use devices will have been replaced by those just being introduced for commercial use today or those on the near horizon – new vehicles, industrial processes and heating systems, and parts of the housing stock and infrastructures. Many power plants will have been replaced, and others will be nearing the end of their useful lifetime.

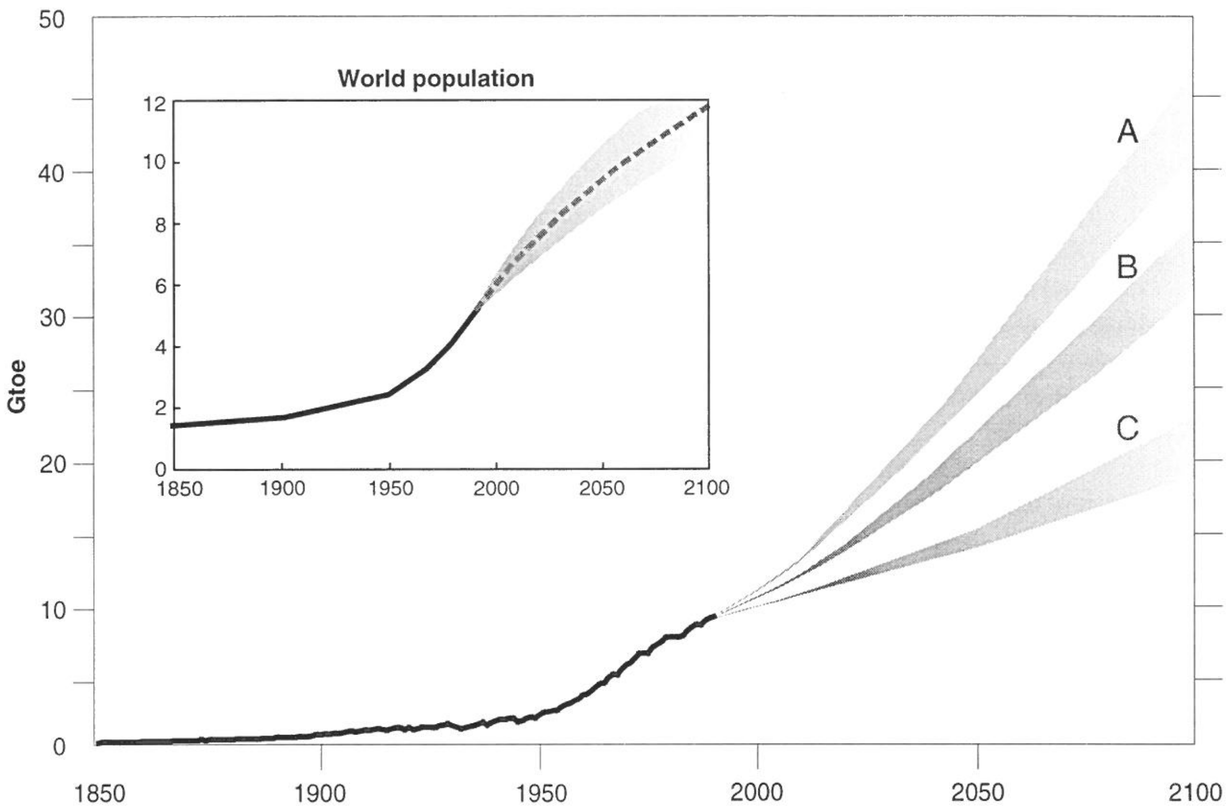

Figure 4: Global primary energy use (Gtoe), from 1850 to present, and projections in the three cases to 2100. The insert shows global population growth, from 1850 to present, and its projection (Bos *et al.*, 1992) to 2100 in billions of people.

The time horizon to 2050 and on to 2100 means that all energy technologies and devices, as well as most energy infrastructures, are likely to have been replaced at least twice. Such turnover offers enormous new supply and end-use opportunities reflected in the scenarios of the study.

Primary Energy

Figure 4 illustrates world primary energy use and world population growth from 1850 to the present, together with the six scenarios grouped into three cases, labeled A, B, and C. Primary energy requirements of the scenarios within each case are almost identical (see *Table 6*).

The three cases indicate that global primary energy use would increase up to three-fold by 2050 and two- to five-fold by 2100. Case A (High Growth) portrays primary energy growth rates continuing as they have since 1850, while Case B (Middle Course) and Case C (Ecologically Driven) present substantially lower growth. Case C, in particular, represents a radical change, with emphasis on energy efficiency and conservation that results in a clear decoupling of energy and economic growth.

Current developing countries account for the overwhelming proportion of the increase in global primary energy requirements. Energy demands increase modestly in the industrialized North in Case A, grow marginally in Case B, and actually decline in Case C.

Table 6: Characteristics of three cases and the six scenarios for the world in 2050.

	Case A			Case B	Case C	
	A1	A2	A3		C1	C2
Primary energy, in Gtoe	25	25	25	20	14	14
Primary energy mix, %						
Coal	24	32	9	21	11	10
Oil	30	19	18	20	19	18
Gas	24	22	32	23	27	24
Nuclear	6	4	11	14	4	12
Renewables	16	23	30	22	39	36
Resource use 1990–2050, in Gtoe						
Coal	235	324	180	226	143	141
Oil	323	302	284	257	210	210
Gas	241	247	285	227	210	197
Energy sector investment in trillion dollars	1.2	1.7	1.2	1.1	0.7	0.7
US dollars/toe supplied	50	67	47	56	50	50
as % of GWP[a]	1.2	1.7	1.2	1.5	0.9	0.9
Final energy, in Gtoe	17	17	17	14	10	10
Final energy mix, %						
Solids	16	19	18	23	19	20
Liquids	42	36	33	33	34	34
Electricity	17	18	18	16	18	17
Other [b]	25	27	31	28	29	29
Emissions						
Sulfur, megatonnes sulfur[c,d]	23	86	15	35	4	3
Nitrogen, megatonnes nitrogen[d]	21	55	21	22	14	12
Carbon, GtC	12	15	9	10	5	5

[a]Gross world product.
[b]District heat, gas, and hydrogen.
[c]Unabated sulfur emissions in Case A could be three (A1) to five (A2) times higher leading to unacceptable local and regional environmental impacts.
[d]Preliminary global estimates.

Table 6 sets out the basic figures by 2050 for primary energy supply and demand, the fuel mix, and final energy demand of the six scenarios. Investment and emissions implications are also provided; these topics are dealt with later in the paper.

Figures 5 and *6* show the changing primary energy mix of the six scenarios. *Figure 7* provides the cumulative fossil fuel requirements, from 1990 to 2050, for the six scenarios. *Figure 8* shows the converging structure of final energy use in the cases/scenarios.

All six scenarios show that the peak of the fossil era has passed. Fossil fuel consumption will grow more slowly than total primary energy needs. Even in Case A, Scenarios A1 and A2, the share of fossil energy declines after 2020. The two most important transitional fuels – oil and natural gas – face declining shares during the next century. In absolute volumes, however, requirements increase considerably compared with current levels.

The scenarios suggest that the world may now only be one-third of the way through the oil age, and one-fifth through the natural-gas age. Even the low-coal Case C Scenarios suggest that as much coal will be used between 1990 and 2050 as was used between 1850 and 1990. Views that these energy scenarios threaten the immediate or early demise of oil, gas, or coal are therefore seriously misplaced.

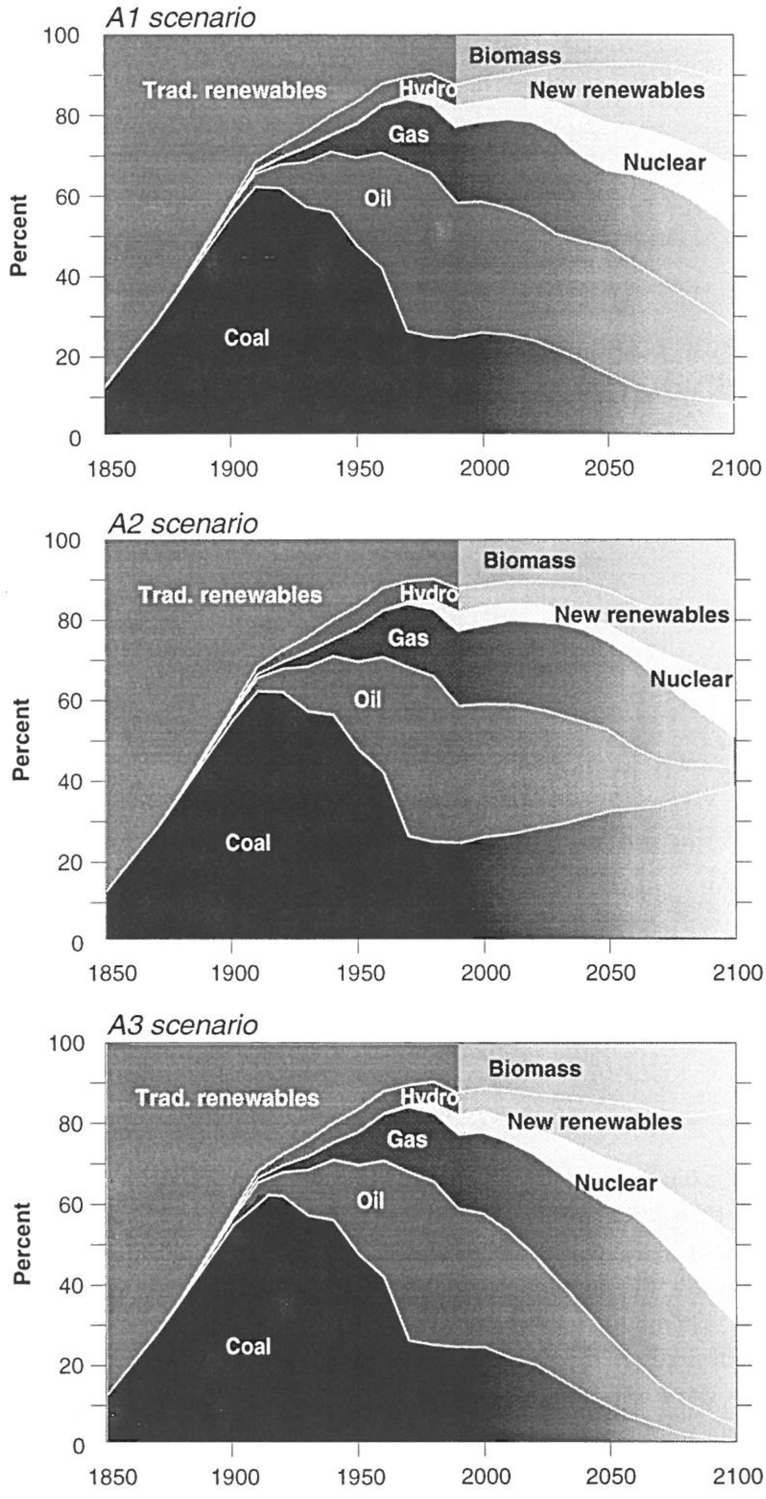

Figure 5: Evolution of primary energy shares, from 1850 to 2100, for Case A: the "clean fossils" Scenario A1, the coal-intensive Scenario A2, and the "bio-nuc" Scenario A3.

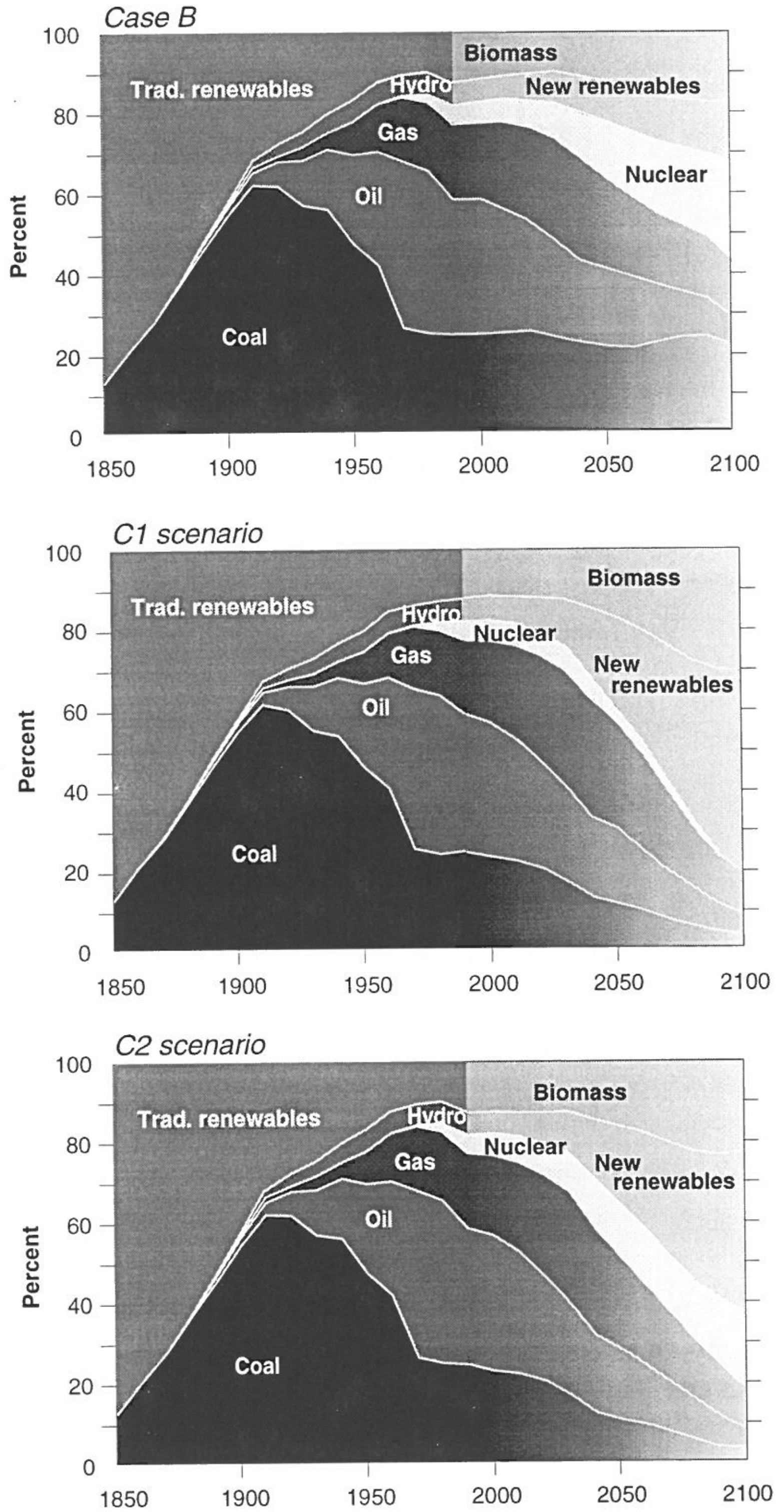

Figure 6: Evolution of primary energy shares, from 1850 to 2100, for the Middle Course Case B, the "nuclear phase-out" Scenario C1, and the "bio-nuc" Scenario C2.

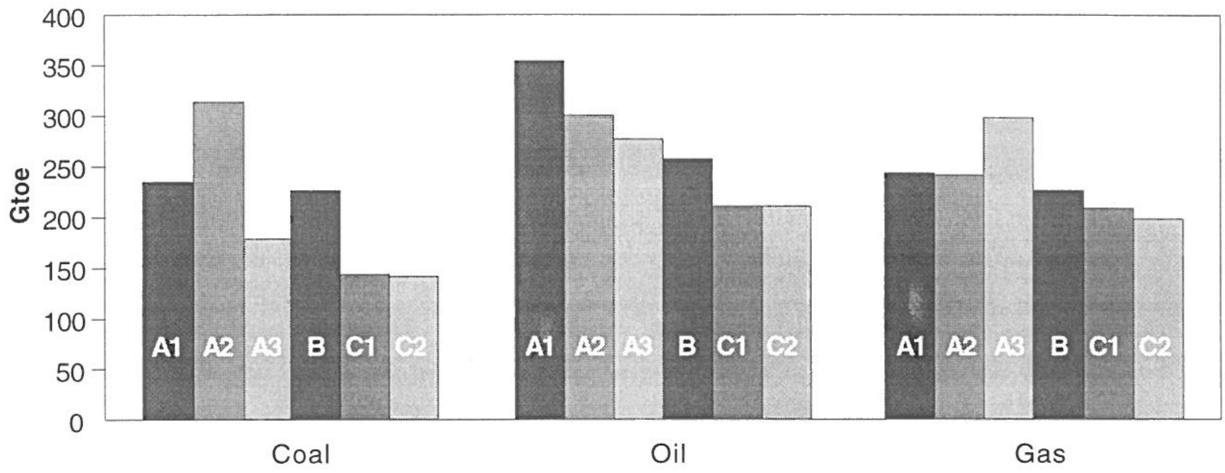

Figure 7: Cumulative fossil energy requirements, from 1990 to 2050, in Gtoe.

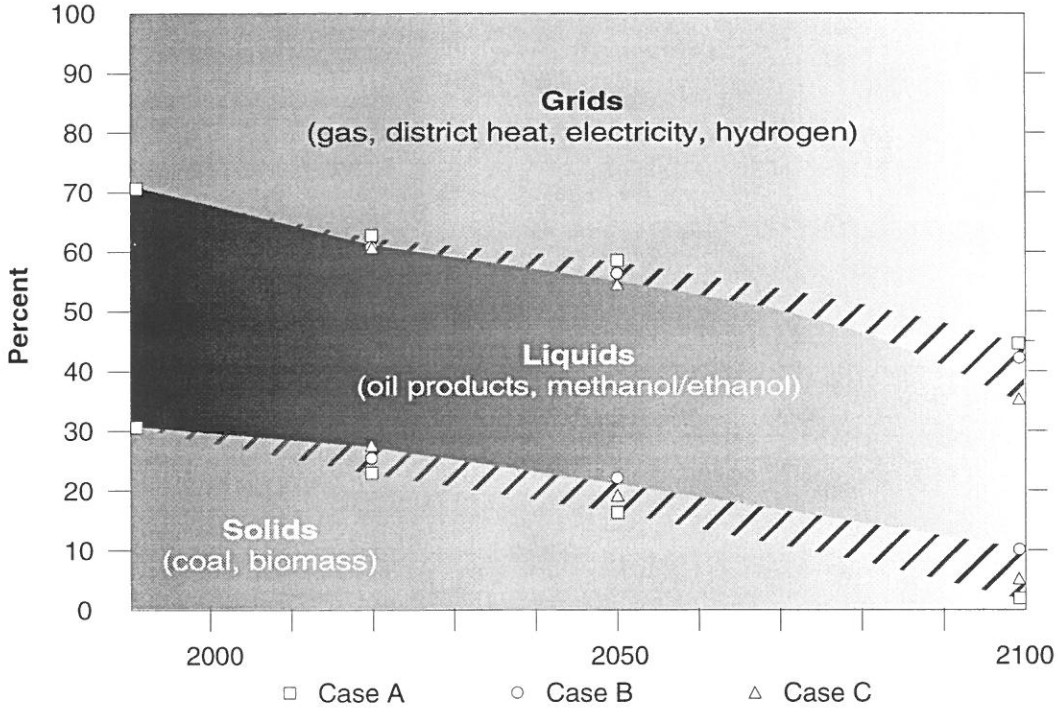

Figure 8: World supply of final energy by form: solids (coal and biomass), liquids (oil products and methanol/ethanol), and grids (gas, district heat, electricity, and hydrogen). Overlapping shaded areas indicate variations across Cases A, B, and C.

The three variants of the high-growth Case A result in between 1,300 and 2,000 Gtoe of fossil energy being consumed by 2100, of which oil and gas comprise 900 to 1,200 Gtoe. This finding relates to the 1,300 Gtoe fossil reserves figure given in *Table 5* and to a fossil resources figure of some 3,800 Gtoe.

In all scenarios there is also a significant expansion of renewables, but the driving forces vary. Case B represents the most cautious assessment of renewables' prospects. Over the extended long-term, however, renewables expand at a steady pace in all scenarios. Even in Case B renewables contribute

22% (4.4 Gtoe) of world primary energy consumption by 2050 and 33% (11 Gtoe), by 2100. In Case C and Scenario A3, renewables reach as much as 22 Gtoe by 2100, with biomass assumed to contribute over 8 Gtoe which raises doubts about its viability due to competing land uses and local environmental impacts, as well as the competitiveness of other energy sources. These issues are discussed in more detail in the full report (IIASA and WEC, 1995).

Scenario A3 requires the installation of up to 75 new nuclear reactors per year to 2050, which implies that public opinion has become convinced of the safety and general acceptability of nuclear-power generation. In Scenario C2, nuclear power grows to a market share of 12% worldwide by 2050 and 19% by 2100 on the basis of new, small-scale, decentralized technologies. In the absence of radical improvements in public acceptability, technology, and economics, nuclear energy might prove a transient technology, as illustrated in Scenario C1.

Relatively rapid and substantial technological change accompanies the comparatively high economic growth and energy requirements of the Case A Scenarios. Scenario A1 assumes that this technological change permits the utilization of large volumes of both conventional and nonconventional oil and gas resources, improved energy efficiency, and mitigation of most environmental impacts. Fossil fuels still account for about 50% of primary energy consumption in the year 2100. Scenario A2 is more conservative about technological change and resource availability; this is the main reason why this scenario is more coal intensive. Scenario A3 is technology intensive, but new renewable energy sources and new nuclear technologies combine to permit the transition to a post-fossil age. By 2100 in Scenario A3, fossil fuels account for 30% of world primary energy consumption; almost all of this is supplied by natural gas.

The single scenario Case B (Middle Course) is the most cautious with respect to economic growth, energy availability, and technological change. Fossil fuels still account for about 45% of world primary energy consumption in 2100, but unless rather dramatic changes occur to tap new fossil fuel discoveries or expand nonfossil energy sources, resource scarcities will become likely. Financing and environmental constraints are likely to be particularly severe in this case as increasingly remote and dirty fossil fuel resources must be exploited and converted to synfuels on a large scale.

The Ecologically Driven Case C Scenarios offer the greatest challenges, but also opportunities, as the emphasis shifts to accelerating energy efficiency, encouraging energy conservation wherever appropriate, and promoting new, decentralized, and environmentally benign technologies. In addition to the vigorous control of local and regional pollutants, a global regime to control the emissions of greenhouse gases is established. The goal is to reduce anthropogenic CO_2 emission levels to 2 GtC by 2100 (about one-third their current level). This action is expected to lead to eventual stabilization of atmospheric CO_2 concentrations.

Case C outlines pathways for achieving the transition from the current dominance of fossil fuels to the dominance of renewable energy flows. By 2050 renewables account for 40% of world energy consumption, a share that increases to over 80% by 2100. Efficiency and environmental criteria require high-quality energy carriers delivered to end users. Renewable energy sources are therefore transformed into electricity, liquid, and gaseous energy carriers. Fossil fuels are transitional fuels of rapidly diminishing significance. Nuclear energy is at a crossroads in Case C, with new nuclear energy staging something of a revival in Scenario C2. In Scenario C1 nuclear energy is a transient technology that becomes virtually phased out by 2100.

All of the scenarios illustrate an expected drive by consumers for more flexible, more convenient and cleaner final energy forms than those available today.

Final Energy

Electricity is already an important energy carrier, and its contribution increases in all six scenarios. Methanol is also expected to play an important role in the future. Hydrogen is another energy carrier expected – eventually – to play a significant role, but mainly after 2050, as considerable time is required to improve its economic performance and build up a hydrogen infrastructure. Overall, the pattern of final energy use is remarkably consistent – and converging – across all scenarios.

The most obvious shift is from energy used in its original form – whether traditional biomass, coal, or some other form – to elaborate systems of energy conversion and delivery. Energy delivered by pipelines and networks plays an increasing role.

There are some important implications for energy efficiency in these shifts, and challenges to traditional conventions and definitions. Hydropower, for instance, is converted into electricity at actual efficiencies approaching 90%, but a standard convention bases the conversion efficiency on the amount of fossil fuel that would have been required to produce the same amount of electricity – the substitution method. This reduces hydropower efficiency to an average of 38.5%, a definition used by WEC (1993) for all nonfossil sources of electricity. The more elaborate energy conversion systems become, the more significant this difference is. The conventional accounting approach has been used in the study, but produces relatively low results with strong implications for renewable energy (photovoltaic efficiency is reduced to 18% if solar is considered a primary energy input; wind energy becomes even more problematic).

Financial and Environmental Implications

Financing

The financing requirements of the energy prospects given in all three cases are enormous. The problems of financing energy development are already of great concern in many developing countries. Growing difficulties in accessing official financial assistance from multilateral bodies, overcoming institutional barriers, dealing with inappropriate pricing policies, and handling poor investment returns all raise concerns. Nevertheless, 3% to 4% of GDP is invested in the energy sectors, a ratio which is expected to remain fairly stable; and savings rates are about 24%, on average, in developing countries and 20% in transitional economies. Therefore, provided the necessary institutional and pricing adjustments are made, and returns on investment become sufficiently attractive, there seems no fundamental reason why the finance for energy investments should not be forthcoming.

The availability of international financing will also be affected by how the international trading regime develops. High Growth Case A assumes a strong drive toward free trade; Middle Course Case B incorporates continuing trade barriers, but none which greatly affect energy trade; and Ecologically Driven Case C makes international trade conditional on satisfaction of sustainable development objectives and whether projects and technologies satisfy emerging environmental standards. In Case A, therefore, financing is attracted to where there is political stability, relatively high returns on investment, and promising growth prospects, regardless of the nature of political regimes. Political considerations and regional bloc-trading regimes have their greatest influence in Case B. Financing of approved technologies and environmentally sound energy sources and schemes is not a problem in Case C, but other investments would be heavily regulated.

Table 7 provides the study's estimate for cumulative investments in energy supply and conversion by region and by scenario, for the period 1990–2020 and 2020–2050. These estimates, by convention, include capital for production capacity, for transmission and distribution infrastructures, and for complying with environmental standards. They do not include investments in end-use technologies, which are traditionally counted as durable consumer goods or business investments. However, the fact that the performance of end-use technologies plays such an important role in all cases and scenarios in the study suggests the need for a new approach in evaluating energy-sector investments. Integrated

Table 7: Cumulative investments in energy supply by region, 1990–2020 and 2020–2050.

	Case A[a]		Case B		Case C[b]	
Energy investments	1990–2020	2020–2050	1990–2020	2020–2050	1990–2020	2020–2050
Cumulative, trillion dollars at 1990 prices						
OECD	8	10	7	10	5	4
REFs	3	6	2	5	2	3
DCs	9	18	7	15	6	11
World	20	34	16	30	13	18
As share of GDP, (%)						
OECD	1.1	0.8	1.1	0.9	0.7	0.4
REFs	9.0	4.3	7.9	5.9	7.0	3.9
DCs	3.7	2.3	3.6	2.8	2.9	1.8
World	1.9	1.6	1.8	1.7	1.5	1.1
Per unit of primary energy, US dollars at 1990 prices/toe						
OECD	50	49	51	60	46	42
REFs	56	53	67	74	54	63
DCs	44	49	40	51	42	48
World	48	49	48	56	45	49

[a]Scenario A1; [b]Scenario C1.

resource planning, for example, has begun to extend the traditional energy perspective to take into account investments in end-use technologies.

Between 2020 and 2050, capital requirements grow substantially in absolute terms, but still more slowly than GDP in all scenarios. There is a shift from supply-side investments (included in *Table 7*) to end-use technology and infrastructure investments (which are excluded). If the latter had been included the numbers are likely to have been greater by at least 50%. There are also advances along the technological learning curve and continued improvements in energy intensity which are reflected in the figures of the study (and which tend to reduce future investment needs markedly).

The results given in *Table 7* indicate a range of cumulative capital requirements between 1990 and 2020 of US$13 trillion to US$20 trillion (at 1990 prices). For comparison, the latter figure equals the world GDP in the year 1990. The developing region's share rises sharply from today's 25% to 30% to between 42% and 48%, and becomes the largest energy capital investment market in all three cases. Considering energy investments as a share of "macro-region" GDP, the transitional economies rank the highest with 7% to 9% of regional GDP devoted to energy investments; obsolete energy structures and slow economic revival are the major reasons for this high ranking. Developing countries invest 3% to 4% of GDP in the energy sector, and the OECD region invests about 1%.

Annual capital requirements rise from under US$400 billion in 1990 to US$500 billion – US$750 billion (at 1990 prices) by 2020, and to US$700 billion to US$1,200 billion by 2050. A large share of this investment will still need to be externally financed.

Environmental impacts

Three kinds of environmental impacts have been considered in the study and are addressed in detail in the IIASA and WEC report: local impacts of indoor and urban air pollution in developing countries; regional impacts of sulfur and nitrogen emissions and their potential contribution to acidification; and greenhouse gas emissions, particularly CO_2, and their potential contribution to enhanced global warming.

Local Impacts

There are two important categories of local pollution. First, that arising from poverty: such as poor sanitation, polluted water, high levels of indoor air pollution caused by burning traditional fuels (impacting with particular severity on women, children, and the elderly), and high concentrations of particulate matter in urban areas. Second, pollution of modern origins: resulting from dense motorized traffic and from low-efficiency coal combustion in electricity-generating plants, industries, and homes. Concentrations of suspended particulate matter, lead, volatile organic compounds, tropospheric ozone, and sulfur dioxide widely exceed World Health Organization guidelines, particularly in urban areas.

The study reaches the following conclusions:

- Improving conversion efficiencies in end-use devices has a key role to play in conserving traditional resources such as fuelwood and reducing indoor air pollution.
- Structural shifts away from traditional energy end-use patterns and energy carriers toward efficient, modern conversion technologies and clean energy carriers are urgently necessary.
- There must be a long-term shift toward energy services provided through clean, grid-dependent fuels.

Environmental constraints, together with increasing affluence, are expected to lead to a long-term convergence of energy end-use systems and infrastructures in the direction of convenient and clean energy forms across the scenarios presented here, despite diverging energy supply structures. Local solutions to local problems must be found that are appropriate in nature and scale to local circumstances, until the extended long-term structural changes toward clean energy end-use carriers yield noticeable improvements in local environmental quality. There are variations among the scenarios in their environmental impacts; however, Scenario A2 and Case B – both relatively coal intensive – arouse the gravest concern.

Regional Impacts

Energy emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) have both local and regional impacts. Acid deposition is of particular concern. IIASA's RAINS model (Alcamo *et al.*, 1990; Amann, 1995). was used to calculate unabated scenarios of sulfur deposition in Europe and in South and East Asia. The analysis was carried out for the coal-intensive Scenario A2 and for the Case C Scenarios.

In Scenario A2, in the absence of sulfur abatement, sulfur emissions in Europe would increase by approximately 50% over the next 30 years. Sulfur deposition would exceed 16 gS/m^2 (grams of sulfur per square meter) per year in large areas of Central, Western, and Northern Europe. These findings contrast with the requirements of the Second Sulphur Protocol on Transboundary Air Pollution of the United Nations Economic Commission for Europe, which calls for reduction measures to lower maximum excess deposition to below 3 gS/m^2 per year.

In the rapidly growing economies of Asia the situation is even more dramatic. In the unabated Scenario A2, SO_2 emissions in South and East Asia triple by 2020 in the absence of abatement measures. It should be noted that the implications of current national energy projections exceed even this pessimistic scenario.

In the unabated Scenario A2 ambient air quality in South and East Asia deteriorates significantly in both urban and rural areas, with sulfur deposition reaching double the worst levels ever observed in the most polluted areas of Central and Eastern Europe. Deposition exceeds the critical loads for most of the ecosystems in the region; critical loads are defined as the maximum deposition levels at which ecosystems can function sustainably. The significance of these findings is that, in the absence of emissions abatement, critical loads for economically important food crops in Asia under Scenario A2 are expected to be exceeded by factors up to 10.

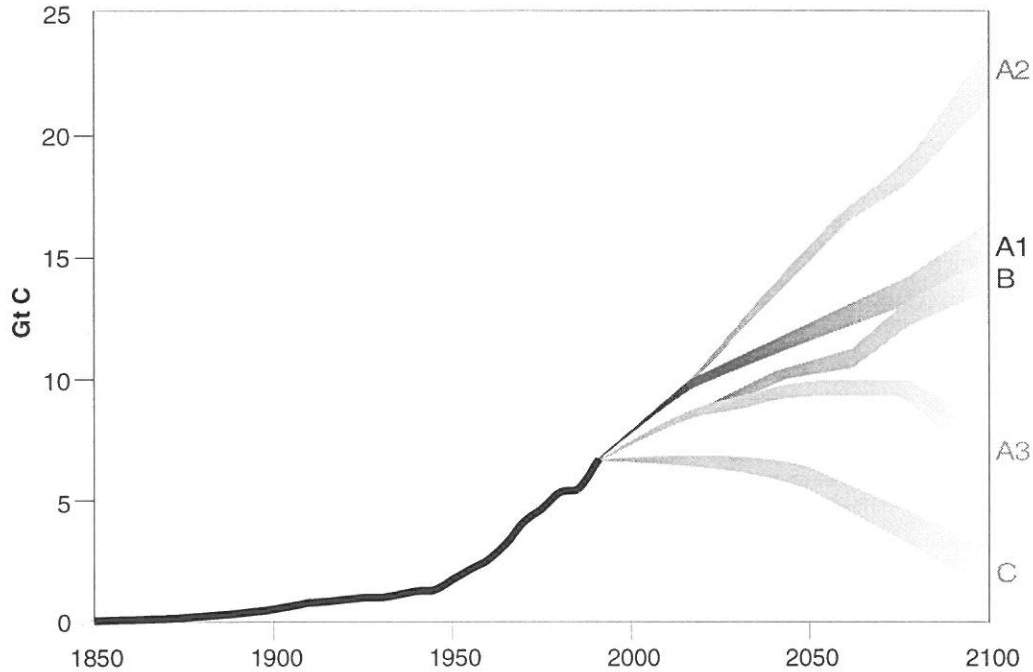

Figure 9: Global energy-related carbon emissions, from 1850 to 1990, and for three scenario families to 2100, in GtC.

Given these results, all the scenarios incorporate only advanced coal technology, including scrubbers for new electricity-generation capacity; sulfur emissions are therefore significantly lower than in the unabated case. In Case A, European emissions in 2020 are between 13 and 15 million tonnes of SO_2 compared to 30 million tonnes in the unabated case. For Asia, Case A emissions in 2020 range from 25 to 45 million tonnes of SO_2, compared with over 80 million tonnes in the unabated case.

Further emission reductions are feasible, but would require substantial additional investment requirements in Case A Scenarios. In Case C Scenarios, energy demand is low because conservation efforts are introduced and much less sulfur-containing fossil fuel is used. These actions would keep the growth of unabated SO_2 in Asia below a factor of two over the next two decades. Consequently, less stringent abatement measures are required, and could be focused more economically on specific local hot spots. Overall, sulfur emissions in Case C can be kept at, or slightly below, 1990 levels with control costs under half those required in Scenario A2.

These results indicate that, in Asia, concerns about sulfur emissions and their potential regional impacts on food security, will take precedence over global, long-term environmental issues such as potential climate change. Nitrogen emissions are likely to have the same relative priority.

Greenhouse Gas Emissions

The study concentrated on future CO_2 emissions as the dominant greenhouse gas for the six scenarios as implied by their level of energy consumption and structure of energy supply. *Figure 9* shows the results.

CO_2 emissions vary substantially from scenario to scenario. In the coal-intensive Scenario A2 they reach 22 GtC in 2100; in Scenario A1, 15 GtC; but in Scenario A3, significant structural change in the energy system reduces the figure to 7 GtC. This last figure is about the same level as current global energy-related carbon emissions, yet the energy consumption would have risen five-fold. Case B's emissions are comparable with those of Scenario A3 up to 2050, but nearly double by 2100. The two

Table 8: A comparison of cumulative emissions (GtC) in the IPCC scenarios and in the WEC scenarios.[a]

IPCC/IS92	IS92 a	1,500
	IS92 b	1,430
	IS92 e	2,190
WEC (1993): *Energy for Tomorrow's World*	Case A	1,425
	Case B	1,130
	Case C	625
IIASA and WEC (1995): *Long-Term Energy Perspectives*	Scenario A2	1,720
	Scenario A1	1,350
	Scenario A3	980
	Scenario B	1,190
	Scenario C1	590
	Scenario C2	580

[a] Based on comparable world population assumptions (UN medium projection).

scenarios of Case C were constrained to stabilize emissions at current levels again by 2050, in order to achieve an emission ceiling of 2 GtC (one-third their current level) by 2100.

In *Table 8* the resulting cumulative carbon emissions (considered of particular relevance for potential climate change) from the study are compared with earlier WEC (1993) scenarios and with comparable emission scenarios of the IPCC (Alcamo *et al.*, 1995; Pepper *et al.*, 1992).

In contrast to many other scenarios, which combine optimism about high economic growth with pessimism about technological change, resource availability (except for coal production), and efficiency improvements, the scenarios presented here offer a more consistent range of possible futures.

The atmospheric CO_2 concentrations and surface temperature warming that might result from the scenario emissions were calculated using a carbon cycle and climate model developed by Wigley *et al.* (1994). *Figure 10* provides the results of the model used for atmospheric CO_2 concentration for the six scenarios. By 2100 the two Case C Scenarios achieve an atmospheric CO_2 concentration below 420 ppmv; Case B is below 580 ppmv; and the three Case A Scenarios are below 520 ppmv (A3), 610 ppmv (A1), and 730 ppmv (A2). Thus only Scenario A2 exceeds the IPCC's "preferred" scenario, IS92a.

There are considerable uncertainties surrounding the implications of such concentration increases for temperature change (as indicated for Case B in *Figure 10*). Case C Senarios show that by 2100 the global mean surface temperature might increase by less than 1.5°C from today's level; the Case A Scenarios and Case B show an increase of between 2.0 to 2.5°C.

These results indicate that, if the current state of knowledge about the radiative forcing from anthropogenic activities is well founded, the energy sector is indeed a major stakeholder. Even in Case C Scenarios, the energy sector would account for 40% of all long-term changes in radiative forcing (including agriculture and deforestation). In Scenario A3 the corresponding figure is 50%, and in Scenario A2 it is 80%.

Conclusions

All six scenarios in the study consider the following convergent and pervasive developments: increasing demand for energy services together with population growth and economic development; increasing quality and environmental compatibility of final energy forms; a shift in the global balance of economic activity and energy use from North to South; and the availability of and reliance on fossil fuels for many decades to come.

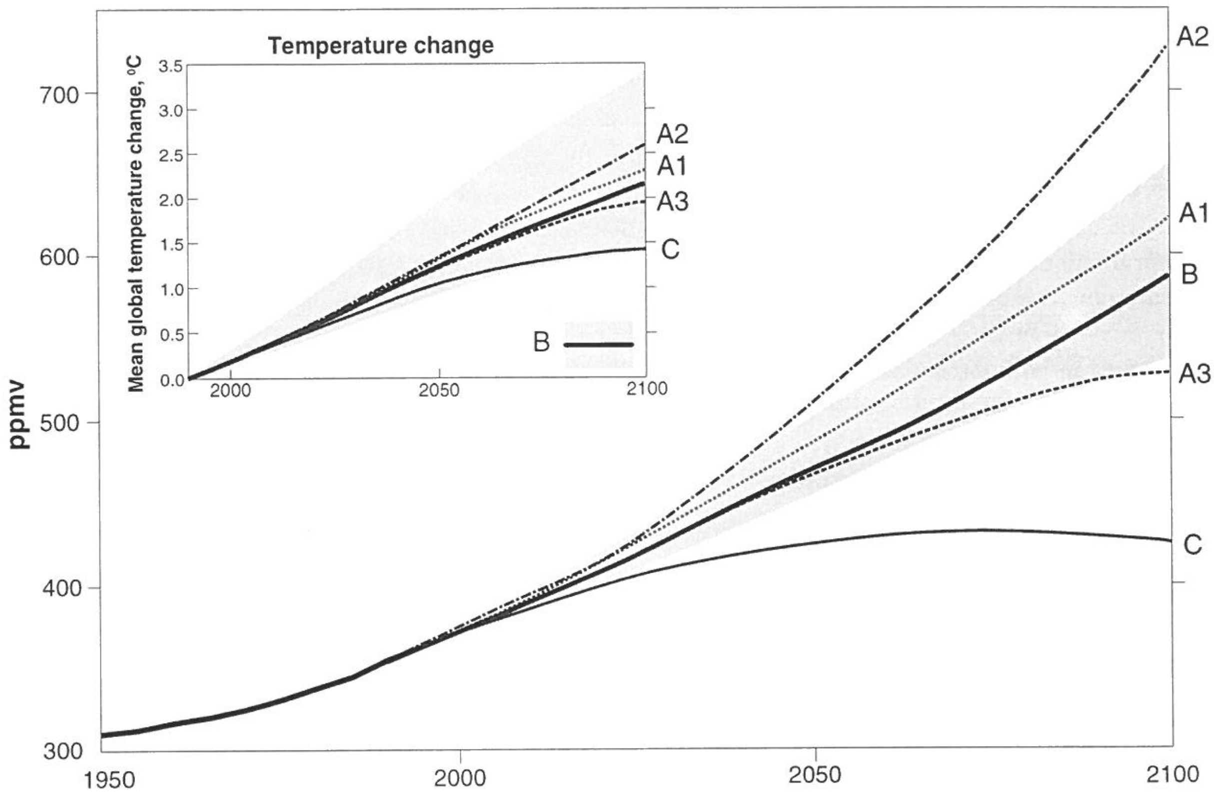

Figure 10: CO_2 concentrations (ppmv), from 1950 to 2100, and global mean temperature change (°C), from 1990 to 2100. The (substantial) model uncertainties are indicated for Case B.

Technological progress and appropriate investment are crucial if we are to match energy sources to the desire for increasingly flexible, convenient, and clean forms of energy required to service consumer needs, but several decades of turnover of capital stock will be required to achieve this match. In the meantime, unless the long-term goal is itself met using the appropriate policies and investment decisions, it will become even harder and more costly to change course than it is today. Investment decisions to 2020 are, therefore, an important concern – not simply because of the tremendous sums of money involved.

Assumptions made elsewhere, that high energy demand growth and limited technological and financial progress are consistent, are questioned in the study. Strict international environmental policy measures (including limits on CO_2 emissions) and policies to promote international equity (Ecologically Driven Case C) prove to be consistent with substantial economic growth and energy development. Although individual countries or sectors may suffer from constraints, the overall result can be a positive sum game, and potential losses can be reduced or averted by strategies to avoid activities that lead to long-run economic decline.

All scenarios show, for instance, that the international oil and natural gas industries are still far from being halfway through their life cycle in terms of volumes extracted and used; even for coal those scenarios that are pessimistic about its use indicate a prospective lifetime of several decades. Thus all three cases, and all six scenarios, reflect substantial growth for all energy industries to at least 2020. The coming decades will see much reshuffling within and among energy sectors. Many new business opportunities will arise that are linked to cleaner and more convenient fuels, to liquid rather than solid fuels, to grid and other interconnected supplies, and to local – often small-scale – energy sources and conversion technologies.

However, the scenarios indicate prospects will diverge after 2020, with different energy industries embarking on often mutually exclusive development paths. Coal, despite its huge resource base, could be particularly threatened by increased competition from other energy sources and by environmental constraints. By contrast, the oil industry and the natural gas industry to an even greater extent have a long future ahead. New markets must be developed for traditional fuels, recognizing that the shift from selling energy to marketing energy services will continue and intensify.

The central message across all six scenarios is that energy end-use patterns are converging toward clean, flexible, and convenient energy forms, while energy systems structures are diverging as a result of emerging opportunities and the availability of policy choices. Although the structural changes in the near term will be modest, the seeds of long-term changes need to be planted now. Near-term investments embodied in both capital stock and knowledge (research and development as well as technology) will determine which of the divergent long-term alternatives will be chosen and which ones will be precluded.

The study has identified patterns that are robust across a purposely broad range of scenarios. It has also described the conditions under which energy systems structures diverge. But no analysis can ever turn uncertainty into reality.

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Systems Analysis of Technological and Economics Dynamics

Presented by

Giovanni Dosi

Project Leader, Systems Analysis of Technological and Economic Dynamics

Technological and Economic Dynamics

Giovanni Dosi, Yuri Kaniovski,[1] *Richard Nelson,*[2] *Sidney Winter*[3]

Introduction

Ideas from biology have interested economists at least since Alfred Marshall began using the term "biological conceptions" in 1907. Increasingly, some economists are turning to the general concept of evolution, if not all the particulars of biological evolution, to answer macroeconomic questions about differences between national economies, how economies change, and how technologies move from country to country and industry to industry; and microeconomic questions about how firms arise, grow, compete, and eventually die. From this evolutionary perspective, large-scale features of economies emerge from the interactions among firms and industries.

IIASA's Systems Analysis of Technological and Economic Dynamics Project (TED) attempts to answer such questions from this evolutionary perspective. Four broad branches of the project – Learning Processes and Organizational Competence; Technological and Industrial Dynamics; Innovation, Competition, and Macrodynamics; and Methodology and Modeling – aim to construct a theoretical basis for a better understanding of economic change, both empirically and with the help of formal models. TED has sponsored several IIASA workshops during the past two years designed to contribute to an evolutionary perspective in economics. The workshops were designed to bring together economists, historians, and organizational theorists from around the world for presentations and discussions of ongoing work. In the meetings, the field of evolutionary economics itself evolves as participants share perspectives, arguments, and refinements. In the following sections, TED researchers offer an introduction to each branch of the project and share insights from three recent workshops.

Two key elements emerge from an evolutionary view of economics. First, neither the economic environment nor individual firms may ever reach a static equilibrium. Both change constantly. Second, although firms may attempt to optimize their structures and procedures, and nations may attempt to optimize their economies, the present nature of firms or economies results from a particular set of past events, milestones on the evolutionary path they have followed.

Learning Processes and Organizational Competence

It seems familiar enough that business firms and other organizations "know how to do things," things like building automobiles or computers, or flying us from one continent to another. On second thought, what does this mean? Does "organizational knowledge" exist, or can only a human mind possess knowledge? If organizational knowledge is real, what principles govern how firms acquire, maintain, extend, and sometimes lose knowledge?

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[1] International Institute for Applied Systems Analysis, Laxenburg, Austria.
[2] Columbia University, New York, NY, USA.
[3] University of Pennsylvania, Philadelphia, PA, USA.

Organizational knowledge

A fundamental assumption of the TED Project is that organizational knowledge does exist, founded on learning by individual human beings within a shared organizational context. This shared context is the key to why an organization's knowledge adds up to something more than the sum of its human parts, and to the ability of organizations to reproduce stable patterns of productive performance, while individual humans come and go. Organizations develop and maintain productive knowledge across a spectrum ranging from routine and repetitive patterns of activity to problem-solving activities requiring specialized analytical skills, and ultimately to shared "mental models" of the organization's place in the world at large.

All these forms of knowledge affect the organization's ability to survive and prosper in its environment – in the case of a business firm, an environment where competition from rival firms typically sets the standard for survival and growth. Knowledge plays a major role in defining the organization's opportunities and constraints. Although adaptive change in the knowledge base may point the way to new activities the firm might undertake, difficulties in phasing out old activities and in pursuing new ones arise. Established routines, analytical frameworks, and mental models are hard to change or abandon. The knowledge base thus plays a quasi-genetic role in economic evolution, ,providing a powerful source of behavioral stability at the firm level, while the selective feedback from the marketplace works over time to sort the successes from the failures.

The TED Project's June 1994 workshop, "The Nature and Dynamics of Organizational Capabilities," was designed to promote an empirically grounded discussion of conceptual and theoretical issues relating to organizational learning and the nature of organizational capabilities. Presentations by researchers studying particular industries provided the group with perspectives on capabilities in a variety of real-world contexts from pizza franchises to computers.

Technology transfer

Some themes emerged in the discussion that facilitate comparative analysis, and may provide guidance for construction of a general theoretical framework for evolutionary economics. For example, the transfer of an advantageous new capability from one site to another may face serious organizational challenges.

Technology transfer problems can arise in any industry. For example, imagine preparing a pepperoni pizza. The straightforward approach of arranging the pepperoni on a bed of shredded cheese fails, because the pepperoni slices begin to drift as the cheese melts. An employee in one outlet of a national pizza chain developed by trial and error a technique that correctly anticipated the dynamics of melting cheese. The pepperoni still floated on molten cheese, but ended up in a pleasing pattern. The new technique spread quickly among outlets with the same owner as the innovating site, but unintentional organizational barriers barred its spread to other outlets in the national chain, despite efforts at promotion.

In the semiconductor industry, a crucial technology transfer step occurs as a chip design graduates from "lab to fab," that is, from the level of prototype production in the design lab to volume production in the fabrication facility. An elegant design that costs too much or designers who will not stop tinkering can block the smooth flow from step to step. Two key procedures promote success in lab to fab transfer: improved communication between engineers in the two locations and ground rules that restrict the freedom to "tweak" a design once it becomes established in the fab.

Organization matters

A point that emerges strongly from these accounts is that organization really matters: Organizational structure and its inherent boundaries present obstacles to transfer that are likely to be insuperable unless organizations specifically and energetically act to overcome them. This observation underscores the validity of a major premise of this part of the TED Project: The study of productive capabilities cannot address only technology in a narrow sense, but must encompass the organizational arrangements through which the work gets done.

Technological and Industrial Dynamics

Today we know much more than, say, 20 years ago, about the mechanisms, opportunities, and incentives that drive technological change in industry. A rapidly growing research literature – to which several members of the TED Project have made significant contributions – is shedding new light on the process by which profit-motivated firms search for new techniques of production, new products, and new organizational arrangements.

Technological learning in a specific marketplace

These search efforts – often doomed to failure, but sometimes reaping impressive rewards – do not occur in an institutional vacuum. There is no such thing as an abstract "marketplace." The opportunities, incentives, and constraints that firms face are embedded in a web of specific linkages with universities, technical organizations, training institutions, regulatory agencies, etc. One of the topics currently under investigation by TED researchers concerns the nature of these institutions and the ways they influence technological advance.

Moreover, at least two general features of technological learning have emerged from this and previous research (these hold from sector to sector and from country to country, despite institutional specificities):

- Many learning activities involve an increasing "easiness" of advance proportional to what is already known, a process called "dynamic increasing returns." In other words, the more you learn, the easier it is to learn more.
- In most industries, learning does not occur in a random direction but is shaped by commonly shared bodies of knowledge, called "technological paradigms." In turn, technological paradigms, once they become established, sometimes yield a basic configuration of artifacts, or dominant designs. Think, for example, of cars or aircraft, televisions or radios. All models share solutions to certain technical problems, such as the transformation of heat into mechanical movements in engines and the broadcast and reception of electromagnetic signals in television and radio. Competition among different products revolves around precisely how well firms carry out these common solutions.

Different sectors, different opportunities

Although these general characteristics of technological progress hold across sectors and national boundaries, some intersectoral and international differences stand out.

For example, the sources of innovative opportunities vary considerably from sector to sector. Some sectors draw directly from advances in scientific knowledge – for example, bioengineering. Others, such as the machine tool industry, draw from more informal experience in design and interaction with customers. And in sectors such as textiles, innovations are mainly embodied in purchased capital equipment and intermediate inputs.

Specific national institutional contexts are also likely to influence the specific forms by which firms learn new technologies. Established firms may dominate new technologies in one context, while new firms do so in another. Furthermore, government procurement or consumer demand may shape "trajectories" of progress.

Several major questions remain: How do technological and organizational changes influence the dynamics of industrial structures, the size distribution of firms, changes in market shares over time, the birth rates and death rates of firms, and the distributions in revealed productivity and innovative performances?

In some sectors, "early movers" get a long-lasting cumulative advantage. For example, the major US automakers dominated for more than half a century, while IBM dominated the computer industry for about four decades. In other cases, past successes appear to hinder efforts to explore new technologies. At least in the United States, established pharmaceutical firms have yet to cash in on biotechnology, leaving the field open for start-ups.

Economic coevolution

The TED Project addresses the general issue of coevolution between technologies, organizational forms, and industrial structures. We ask how particular patterns of industrial change ("learning regimes") influence the economic environment ("industrial structures"), and how the economic environment, in turn, strongly influences both survival rates of firms and the direction of future change.

At the TED workshop held at IIASA in July 1994, scholars from Statistics Canada, the US Department of Commerce, and the Science Center in Berlin, among others, addressed two major issues. First, they attempted a thorough assessment of what we know – and what we do *not* know – about industrial demography and industrial change. They attempted, for example, to sort out the relative contributions of established firms and new firms to productivity growth and employment creation. Second, participants attempted to prepare the ground for a dialogue between evolutionary modelers and empirically minded researchers, groups who rarely compare notes. One of the unique features of the TED Project is to bring these two types of researchers together and give them the opportunity to talk to one another.

Current projects, future applications

Current TED activities include work on several original empirical papers detailing economic regularities, that is, "stylized facts." At the same time, TED researchers are developing models of industrial dynamics that attempt to explain and raise new questions about these stylized facts, with the long-term goal of enabling policy makers to draw policy implications from the models.

Such implications are likely to require fine-tuning to the specific economic situation. For example, under some technological regimes, government and institutional support for research and development might be quite helpful, while under others, it might prove useless. Or, a dominant market share may represent evidence of unfair restrictive practices demanding antitrust measures in one sector or situation, while in another, large size might only represent the advantage of different technological capabilities. Antitrust actions in this situation would mainly imply killing the "hopeful monsters" nurtured by economic evolutionary forces.

Innovation, Competition, and Macrodynamics

The historical record of economic growth over the past two and a half centuries is rich and complex. Sustained growth of worker productivity and per capita income, associated with the development of new technologies and rising capital intensity of production, is a phenomenon that only really began in the last decades of the 18th century.

Discontinuous economic growth

Economic growth rates tended to increase from the early decades of the 19th century to the early decades of the 20th. The period from the end of World War II until 1970 saw even more rapid growth rates in many countries, followed since 1970 by significant slowing. Different eras have been marked by different leading industries. As the leading technologies have changed, the nature of the economic institutions associated with their rapid development has changed as well.

Until the late 19th century, rapid sustained economic growth was almost exclusively a phenomenon of Western Europe and its overseas offspring. Great Britain was the early growth leader, but by the late 19th century, leadership in many fields had passed to the United States and in some fields to Germany. Somewhat later, Japan joined the growth club, followed after World War II by several other countries. Today, much of the world remains economically disadvantaged and dirt poor.

Growth theories

Recognition of the richness and complexity of the economic growth record raises fundamental questions regarding the phenomena that economic growth theory ought to address. It is too much to ask of any theory in economics, or in the social sciences more generally, that it fully explain all aspects of the growth record. Clearly a satisfactory theory of economic growth needs to be able to explain the movement over time of broad aggregate measures, such as gross national product, and to illuminate differences in the growth experiences among countries.

But must a satisfactory growth theory recognize explicitly that different eras are marked by different leading industries? Must it contain a realistic treatment of the processes of technological advance? To what extent must a satisfactory growth theory track the development of important institutions, like the rise of large modern corporations or research universities? While sophisticated historical accounts of economic growth recognize all these variables, more formal growth theories tend to focus on just a few.

A TED workshop

The third TED workshop – on understanding growth as an evolutionary process – took place at IIASA in late June 1995. The workshop followed the format employed in the prior two. Participants considered in detail the empirical phenomena requiring explanation, then moved on to a discussion of broad theory and particular models.

The discussions at the workshop suggested the existence of three very different kinds of economic growth theories. One focuses largely on quantitative statistical aggregates. It is centrally concerned with the relationships between input growth (in particular, growth of capital per worker) and output growth (in particular, output per worker). Technological advance appears largely as a "residual," associated in some recent theories with investments in research and development, human capital, and other quantitative variables. However, theories of this genre tend not to concern themselves with the details of the processes through which technological advance occurs, bringing institutions into the discussion only as qualitative background variables.

While there are fewer representative examples, another genre of growth theory tends to focus on national institutions, seeing these as providing the structure within which technological advance, input growth, and output growth proceed. These theories, including the *Régulation* approach, developed particularly in France, focus on the national economy as a complex economic, political, social, and cultural system that molds relationships among the actors, their expectations, and behavior toward one another.

Evolutionary theories of economic growth, the third genre, tend to have several central, defining properties. First, they focus on the processes involved in technological advance. Second, they focus at least as much on the forces tending to upset equilibrium as they do on the forces tending to move the economy toward equilibrium. Third, evolutionary theorists tend to cast individual business firms in a central role in economic change. Within evolutionary theories, growth of output and capital at a macroeconomic level are treated as the consequences of the microeconomic processes generating and spreading technological advance. As in the first genre of theories, formal evolutionary models tend to treat institutions as important qualitative variables.

Future directions

The workshop focused more on evolutionary theory of economic growth than on the other two broad kinds of theories (but also began investigating possible bridges with the second, institution-centered approach). The central purpose was to identify future directions for further evolutionary theorizing. The following points emerged from discussions.

First, there is a very large gap between verbal statements and formal modeling regarding the central role of economic institutions in evolutionary theory. Economists have made some progress over the last decade in modeling institutions, often using the language and concepts of game theory, and this clearly is one route that evolutionary growth theorists ought to consider. However, the modeling of institutions in evolutionary growth theory remains a challenge.

Second, growth theories in general, and to some extent also many current models in evolutionary growth theory, tend to agree better with data concerning relatively smooth continuing growth than with data concerning turning points or sharp changes in the pace and pattern of economic growth. In this respect, evolutionary growth theory may have a built-in advantage over the other two kinds of growth theory, in that it naturally adapts to techniques of nonlinear dynamic modeling. However, a huge gap remains between demonstrating that a stylized formal evolutionary growth model has the *capability* of generating cycles in growth and divergent behaviors of national economies, and showing that that theory provides an intellectually satisfying and deep explanation for particular changes.

These two broad directions – formal modeling of institutions and a better grip on how patterns of economic growth change – top the agenda for future evolutionary theorizing about economic growth.

Methodology and Modeling

Explaining the process of economic change poses one of the most important challenges to any economic theory. One inroad into understanding change is by means of evolutionary models, in which business firms are the central agents. Firms whose research and development turns up more profitable production processes or products will grow in the market environment faster than their competitors. The competitors, for their part, may at some point attempt to imitate profitable innovations. Firms change continuously, partly by searching for more effective technologies, investment rules, or even improvements of their search procedures. All of these aspects have been referred to as routines. Inefficient firms may fail, while a flow of new firms into the industry continuously introduces more variation into the set of competing technologies and behavioral rules. As a result, the population of firms remains heterogeneous. The future evolution of the industry can only build on existing characteristics, which constrain the outcomes that may (or may not) occur. This mechanism, however, also incorporates a degree of chance. The logic of such models typify what mathematicians call a "stochastic dynamic system," which can be modeled as a Markov process in discrete time and in a high-dimensional space.

A standard cycle

A standard cycle can be described as follows: At one moment in time a firm can be characterized by its capital stock and prevailing routines. These routines determine the inputs and outputs of the firms. The market determines firms' profitabilities and changes in market shares, given the technologies and other routines in use. Profits, together with the investment rules of the firms, determine whether they expand or contract. Search routines implemented by firms attempt to improve some aspects of firm behavior, capabilities, and technologies, and may come up with proposed modifications, which may or may not be adopted. The system is now ready for the next iteration.

Firms in the model behave similarly to the way humans appear to in models of most other social science disciplines, except neoclassical economics. They are influenced by habits, customs, or beliefs. Evolutionary economic theory makes no presumption, as neoclassical theory does, that what firms do is optimal, except that, metaphorically speaking, they attempt to do the best they can. At the same time, firms can discover new behavioral rules or new technologies, and thus they can internally expand the range of operational opportunities available to them.

Modeling evolution

The TED Project has proceeded along two complementary modeling paths. The first includes more phenomenological and behavioral details and relies mainly on simulation techniques. This type of model attempts to show that, with economically meaningful system parameters and behavioral rules, macroeconomic regularities emerge from underlying microeconomic interactions.

The second style of modeling focuses on more stylized and parsimonious representations of the dynamics of technologies, expectations, organizational customs, and behaviors. These changes tend to reinforce themselves, forming a feedback loop that maintains behaviors despite their actual effects on performances. Therefore, small historical events may exert a cumulative impact on future developments, locking in particular configurations of technologies or behaviors, even when they are far from optimal.

Some aspects of these basic models can be studied analytically, leading to exciting mathematical challenges concerning the analytical properties of stochastic dynamic systems. In this respect, classical mathematical results, appropriately modified, are becoming convenient and powerful tools in the study of evolutionary economic processes.

Capturing competition

These models typically produce many possible outcomes, each a result of a dynamic learning process. To capture the underlying competitive process, a wide variety of mathematical approaches has been suggested from within and outside economic analysis, including ordinary differential and difference equations and stochastic differential equations (in particular those with trajectories on the unit simplex replicator equations – or in the stochastic case, urn processes). TED Project members are developing and applying several of these methods of analysis, for example, "Generalized Urn Schemes."

To illustrate an urn scheme as applied to evolutionary economics, imagine a large (in the ideal case, infinite) pool of adopters of two competing technologies, say A and B. When the process starts,

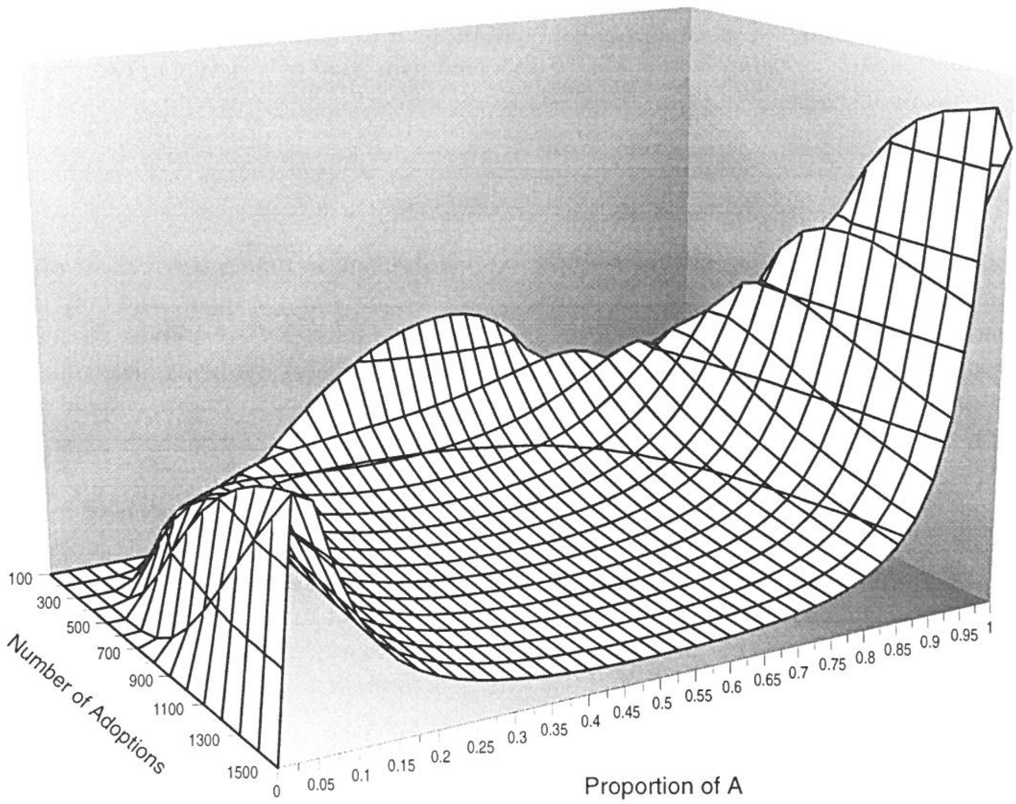

Figure 1: The probability distribution of the proportion of economic agents using technology A as new adoptions are made over time. Technology A starts out with a very slight preponderance (the initial numbers are 18 for A and 17 for B, with a sample size of 5). From a unimodal distribution, the system bifurcates into a bimodal one, with the highest probability for A almost completely dominating, a substantial probability for B dominating, and very low probabilities for coexistence. In the limit, the distribution becomes a binary one concentrated at the two extreme points.

some adopters use A and some B. Because potential adopters are less than perfectly informed about the two technologies, they use probabilistic rules for deciding which technology to adopt. For example, they might use a majority rule: Take a sample of those already using the technologies and choose the one the majority uses. The sample size reflects the extent to which adopters get along with and imitate their friends and neighbors in the economic neighborhood (see *Figure 1*).

As more agents adopt one of the two technologies, the relative shares of the technologies may reach a relatively stable final state. If the process of adoption begins with more agents using technology A, A is more likely to end up being more widely used. In some cases, A will dominate even if it competes with an "objectively better" technology. In any case, randomness affects the final state to which the system converges.

This simple, basic scheme can be applied, with appropriate modifications, to so-called evolutionary games with incomplete information. Consider two groups of economic agents repeatedly playing a game in which the agents have only incomplete information about the payoffs (the outcomes of their actions). The fact that agents do not know with certainty how successful their previous strategies have been introduces a random element into the process. Nonetheless, agents adapt as the game continues and may discover consistent solutions after sufficient time has elapsed.

Urn schemes allow the analysis of adaptive learning processes, in which, for example, one group of agents tries to infer "what is best to do" from the second group and vice versa. Each agent changes its strategy continuously during the process. Will the dynamics converge to some stable "conventional" behavioral pattern? Or will the system continue to fluctuate over time? And if it does converge, what are the properties of the "conventional" behavioral pattern? A current collaboration between TED and Dynamic Systems Project members addresses these issues.

Current and future connections

TED's contributions to the analysis of economic evolution link with parallel developments in other fields of research, such as the evolution of complex structures in biology and theories of adaptive learning and emergent computation. At the same time, the TED Project is currently developing a library of computer program modules for the simulation of evolutionary models. These modules will allow researchers to use learning processes and market interaction mechanisms with conditions drawn from existing models and also to experiment more easily with new ones. Within about two years, TED researchers hope to create unified software addressing a range of models. This should allow scientists inside and outside of the TED network to run their own simulations, possibly discovering new patterns of complex economic behavior.

International Environmental Agreements for Sustainable Development

Presented by

Owen Greene

Research Scholar, Implementation and Effectiveness of International Environmental Commitments

International Environmental Agreements for Sustainable Development

Owen Greene

Introduction

At UNCED in 1992, the international community agreed upon an ambitious program to promote sustainable development. Sustained international cooperation is useful or essential to implement most aspects of this program. There are now at least 120 relevant international environmental agreements, and more are expected. Of these, some are "dead letters" and others probably simply include obligations to do things that would have been done anyway. However, case studies have established numerous cases of "effective" regimes; that is, regimes that have affected behavior and outcomes, and at least to some extent have helped to tackle the problem for which they were established. The Implementation and Effectiveness of International Environmental Commitments Project (IEC) at IIASA is concerned with improving understanding of factors that increase (or decrease) the effectiveness of international environmental regimes.

In principle, the development of international efforts to tackle environmental problems can be divided into several phases, though in practice these often overlap and the process is not linear. The three main stages can roughly be characterized as agenda formation, negotiation and decision making, and implementation.

The agenda formation stage includes the processes by which the problem becomes recognized, emerges onto the political agenda, is framed for consideration and debate by the relevant policy communities, and rises high enough on the political agenda to initiate negotiations and decision-making processes. The negotiation and decision-making stage takes an issue from the point where it becomes a priority item on the agenda of relevant international policy-making or negotiating fora to the point where agreements are achieved on which principles, rules, commitments, and programs will be adopted to tackle the issue, and thus (implicitly at least) how the costs and benefits will be distributed. The implementation phase includes all of the activities involved in implementing the decisions and policies adopted in response to the problem. These can include the establishment of relevant laws, regulations, and financial incentives; the development and operationalization of agreed programs; and all other measures aimed at changing social practices appropriately.

Each phase involves a range of complex processes, and experience shows that it is very uncertain whether an issue even makes it through the agenda-formation stage, let alone through to successful negotiation and agreement. In practice, most research on the development of international responses to environmental problems has tended to focus on the processes of negotiation. But it is also vital to study questions of implementation and effectiveness.

The implementation stage is typically no less complex and difficult than the other two. On the contrary, experience shows that it is one thing to negotiate an agreement and quite another to bring it into operation and to achieve the desired effects. Those charged with implementing the decisions may lack necessary commitment or resources, and will typically interpret the decisions in their own ways.

Actors whose interests are substantially affected by the changes in policy can be expected to continue to try to influence these policies and the ways they are implemented. Compliance may leave much to be desired, and in any case the actual effects of decisions can be very different to the expected ones. Finally, knowledge about the problem is normally incomplete in the first place, and thus the decisions and adopted policies may turn out to be less adequate than initially thought. For these and other reasons, once an agreement has been established, efforts to strengthen or develop it typically continue alongside the implementation activities.

The IEC Project at IIASA focuses on what happens after agreements have been reached: What factors determine whether and how they are implemented and developed, and when do they make a difference? The answers are important for policy makers as well as researchers, because they can be used in efforts to design more effective agreements and implementation policies.

The Project is conducting several historical case studies on factors determining the implementation and effectiveness of international agreements on acid rain, ozone depletion, regional sea pollution, whaling, ocean dumping, wildlife protection, access to genetic resources, food safety standards, and trade in hazardous chemicals and pesticides.

Three types of questions or issues have been singled out for particular attention.

- First, patterns of participation in the making and implementation of agreements: How they are determined and what are their implications for effectiveness?
- Second, implementation problems in countries in economic transition, especially in Russia.
- Third, the significance and role of international processes by which national implementation and compliance are monitored and reviewed.

A further important part of the project is the development of a data base of key variables that are relevant to the effectiveness of international regimes. The aim is to code 50–60 well-studied international agreements, to provide a basis for systematic comparative research to identify the main factors determining regime effectiveness. The development of the protocol for the data base is now in its final stages. When the data base is complete, it will be available to all interested researchers.

The following sections briefly outline some aspects of the work done so far.[1] Further findings, relating to the implementation and effectiveness of international agreements to tackle some specific environmental problems, will be presented at the Symposium. The next section provides a brief review of some definitions and some of the basic findings on environmental regimes from previous studies.

A Review of Previous Findings on Environmental Regimes

The exact definition of an international "regime" is still contested among specialists, and some skeptics doubt whether "regime theorists" are really clear on what they are talking about. Nevertheless, a broad understanding of an international regime as "an international social institution with (more or less) agreed-upon principles, norms, rules, procedures, and programs that govern the activities and shape the expectations of actors in a specific issue area" probably provides a good enough basis for proceeding to examine the processes by which the international community has responded to particular environmental problems. (The discussion in this section draws on several publications produced by the IEC Project, particularly Levy *et al.*, 1995; Greene, 1995.)

The notion of an institution is broadly conceived in this definition; it refers to established and structured social practices rather than simply to an organization. On the one hand, this means that a regime is understood to be broader than a specific organization or agreement, because it includes all formal or informal international institutions, guidelines, rules, programs, and practices directly associated with its operation. On the other hand, it is narrower than a broad international convention (such as the liberal international economic order): it is constituted by relatively specific norms, procedures, or institutions developed to address a particular issue area.

Even accepting such a working definition, some nevertheless doubt that regimes matter. For example, some take a strong "neorealist" view that international society consists of sovereign states whose interactions are dominated by the pursuit of power and predetermined interest, and that the outcomes of these interactions are dominated by the underlying distribution of power. Such neorealists generally regard international agreements and institutions as epiphenomena that have no substantial independent effect. Doubtless this is sometimes true. However, nobody knowledgeable about international environmental regimes can reasonably maintain that none of them matter. Case study research has established numerous cases of "effective regimes" – that is, regimes that have shaped the behavior of a range of international, transnational, and domestic actors, affected outcomes, and at least to some extent helped to tackle the problem for which they were established.

International cooperation is useful or essential for tackling many transnational environmental problems. Agreements negotiated by states and the development of institutions involving influential international and domestic actors are key ways in which such cooperation can be organized and maintained. They provide an important framework for the interaction between international and domestic actors and processes, and between "knowledge," power, and interests relevant to a particular issue area. Moreover, a regime provides a focal point for the formulation and implementation of policies to tackle a particular transnational environmental problem.

Moreover, contrary to some of the early propositions about the character and formation of international regimes these regimes come in a variety of different types. They can form and operate in a wide variety of circumstances and in the absence of hegemonic powers. Moreover, once established they can survive and influence shifts in the distribution of power in international society, and can persist even if their obligations become inconvenient to one or more powerful states or if there is a deterioration of overall relations between their participants. Thus at least a number of regimes have been shown to be much more than epiphenoma: regimes can be robust and can have significant consequences.

Knowledge, power, and interests all play a key role in determining when and how regimes develop and the consequences they have. So do values, resource transfers, institutional capacity, social learning, individual leadership, and international context. The relative importance of these factors changes as the regime develops through the various stages outlined. Moreover, their relative importance is likely to be regime-specific and, to a significant extent, historically contingent.

States are typically the formal members of regimes, but many case studies have demonstrated that non-state actors are often very important in the formation and development of international environmental regimes. In relation to implementation processes and regime effectiveness, the links between international environmental institutions, states and non-state actors, and processes appear to be particularly important and complex (though less research has been carried out on these). In other areas, such as arms control or trade, agreements mostly directly aim at regulating government action. The mechanisms by which governments can ensure domestic implementation are typically well developed and relatively direct. In contrast, implementing environmental commitments often involves the complex task of changing the practices of a wide range of non-state actors, semi-autonomous state industries or agencies, or local authorities.

To be effective, regimes must make a difference. More precisely, their institutions, rules, and procedures must alter external facts or processes (either directly or indirectly through their effects on the patterns of power, interest, influence, knowledge, values, resource transfers, and institutional capacity) in ways that change the behavior of environmentally relevant actors. Thus, it is not enough to examine institutional design or external factors separately. The key element is how they interact. The effectiveness of regimes depends on the extent to which a combination of these institutional characteristics and mechanisms are developed so that they influence and interact within a way that promotes desired changes in behavior.

There is a range of characteristics of an international environmental institution that could be important in determining effectiveness. The nature and formulation of the rules and commitments of the regime can be important, including the ways in which politically and legally binding provisions are combined and the mechanisms by which rules are developed or revised. For example, it has been shown that compliance with MARPOL rules to limit oil pollution from tankers became much better when efforts focused on technological regulations relating to tanker construction and port facilities instead of operational rules relating to the conduct of operators at sea. The distribution of ownership rights can be similarly important: the establishment of Exclusive Economic Zones and the designation of deep seabed resources as "common heritage of mankind" as part of the third Law of the Sea regime is an important example of the way regimes can aim at allocating ownership rights to contribute to the management of environmental resource problems.

The structure and role of the international secretariats or organizations associated with the regime can also be important. For example, a professional and relatively autonomous secretariat can play a significant leadership role and facilitate the effective operation and development of the regime. UNEP played a key role in the formation and early development of the regional seas and ozone conventions.

Mechanisms for resource transfers among participants can critically affect patterns of interest and capacity among participants. The ways in which scientific and technical knowledge generation and advice are institutionalized can affect learning processes, distribution of influence, and the development of epistemic communities. Similarly, the design of consultative and dispute resolution mechanisms can make a big difference in whether problems or concerns tend to be neglected or to escalate damagingly, or whether they are routinely tackled in a timely and constructive way.

Finally, participation and access, monitoring and implementation review, and stability of property rights and institutional capacity-building mechanisms are all potentially important. These are discussed below. However, it is important to note that the effectiveness of a regime depends on the extent to which a combination of these institutional characteristics and mechanisms are developed so that they influence and interact within a way that promotes desired changes in behavior. Above all, the effectiveness of an environmental regime typically depends upon its capacity to develop and adapt. To be effective, the institutions, principles, rules, and procedures of a regime must directly or indirectly alter knowledge, patterns of interests and power, the activities and capacities of actors, and social processes in line with its goals. The extent to which it does so will depend on the ways its institutional design (rules, procedures, obligations, resource transfer mechanisms, etc.) engages with the "external" world. It must, therefore, adapt to external developments, some of which it will itself have shaped or brought about.

Access and Participation

What factors affect participation in the implementation of environmental agreements, and how do different patterns of participation influence the effectiveness of international agreements?

Environmental policies involve and affect highly dispersed agents such as individuals, firms, environmental pressure groups, government agencies, and other organizations. Effective implementation may require wide participation; democratic styles of policy making that stress accountability and transparency further foster wide participation. Yet wide participation yields problems of coordinating large numbers of diverse interests. Countries have evolved different styles of managing participation, thus allowing direct comparisons: for example, the Project's study of North Sea pollution is a comparison of implementation of environmental measures in the United Kingdom, the Netherlands, and Norway. All three are giving effect to the same North Sea agreements but with different domestic styles of participation, ranging from relatively closed in the United Kingdom to open in the Netherlands; Norway is a mixture of the two. These countries are also the subject of another case study on the implementation of nitrogen oxides abatement that is part of the European effort to limit acid rain.

The Project's case studies on Russia's implementation of measures to clean up the Baltic Sea and to limit acid rain show how the social and political transformation in the former centrally planned economies has dramatically changed the styles of participation, with mixed results. In some cases, new possibilities for participation in the implementation of pollution abatement has allowed enterprises to work directly with sources of funding needed to finance abatement. In other cases, social transformation has spawned a gridlock of dozens of new enterprises and overlapping regulatory bodies.

Participation also varies at the international level. A case study on "soft law" explores, for example, how the flexibility of nonbinding agreements allows for active management of participation. The non-binding agreement to control trade in hazardous chemicals and pesticides has evolved a different pattern of access for nongovernmental organizations than the major legally binding environmental agreements. In addition to exploring participation by nongovernmental organizations, the case study on the whaling regime explores how changing participation by states has changed the content of the agreement, notably from the goal of maximizing the harvest to (now) the elimination of whaling. The ways in which participation at the international and domestic levels is managed may point toward new strategies for improving the making and implementation of environmental agreements.

Implementation in Countries with Economies in Transition (CEIT)

How has the transition from central planning, especially in Russia, influenced implementation of international environmental agreements?

First, I give some brief observations of these processes of "transition." It is clear that the states of Eastern Europe and the former Soviet Union have been undergoing a profound process of economic, social, and political transition. Nevertheless, it can be difficult to define what is exactly meant by "transition" in our context. Five elements appear particularly important: rapid changes in the political systems; rapid changes in the economic systems; economic collapse (at least temporarily); uncertainty in current and future regulatory systems and in the ownership of companies and resources; and cultural and value changes. Each could have a major impact on the implementation of international environmental commitments. The IEC Project aims to clarify these impacts and to provide lessons for the future.

Case studies include the implementation (by the Soviet Union and Russia) of policies to control emissions of sulfur dioxide in the Russian territory. The Project is also conducting a detailed study of the same issue on the Kola Peninsula; recently the downwind states of Sweden, Norway, and Finland have attempted to conclude deals directly with major Kola polluters to reduce emissions in exchange for technology and other resources. A third case is the effort by Russia and the Baltic States to implement measures to comply with the agreements to reduce pollution in the Baltic Sea. All the cases explore how instability and change in property rights affects pollution-related investments. The Kola and Baltic Sea cases also explore how external financial transfers and the ability to leverage domestic resources influence the type and level of pollution abatement, and how the practical lessons from these experiences should influence the design of new financial instruments.

Because implementation in Russia is strongly affected by the legacy of central planning, in 1995 the Project initiated an additional case study on the implementation of international wetlands and endangered species agreements in Russia. Unlike the implementation of sulfur dioxide controls, where the influence of industrial planning during the Soviet era was (and remains) strong, these other issues are characterized by different legacies of (mostly weaker) central planning. All of the studies in Russia are conducted with a common detailed research protocol to yield results that are comparable. This is essential in a context where so much is in flux that it is difficult to trace the specific effects of international agreements and efforts to protect the natural environment.

The Role and Significance of Implementation Review Mechanisms

How can mechanisms and processes for monitoring and reviewing implementation and compliance promote the effectiveness of environmental regimes?

Implementation review processes are the processes by which regime participants collect, exchange, and review information relating to implementation and environmental performance. Implementation review in environmental regimes typically involves a wide range of informal and formal processes. Individual governments or informal groups of states may engage in independent monitoring and assessment of the other participants environmental performance. There is also normally a wide range of nongovernmental monitoring and review activities involving all sorts of expert or interest groups.

Nevertheless, numerous international environmental agreements have set up formal provisions or procedures for reporting, monitoring, and implementation review. Where they operate, these can affect implementation through a wide range of possible mechanisms, operating at the international, transnational, and domestic levels, by deterring noncompliance, building confidence, promoting learning, affecting patterns of interests and power, and facilitating coordinated action in response to poor implementation (Ausubel and Victor, 1992; Greene, 1993; Victor *et al.*, 1994; Greene, 1994; Greene, 1995).

For example, since most agreements and institutions are only imperfectly adapted to the situation, regimes should have the capacity to develop in the light of experience with implementation and changes in knowledge about the problem and the adequacy of existing commitments, policies, and measures. This is one of the reasons why reviews of implementation and environmental performance are important for regime effectiveness.

A regime is created, developed, and managed by a complex of interested actors and institutions, mainly through the Secretariat, Conference of the Parties, and other bodies. To the extent to which they have an interest in the effectiveness of the regime, these actors will aim to develop and adapt the regime appropriately. They will also aim to identify and respond to implementation problems in a timely and effective way within the existing regime. This is another way in which implementation review processes are important for regime effectiveness.

Whether and how regime participants successfully respond to and deal with implementation problems will depend partly on regime design. Verifiability, transparency, and the existence and character of established institutional mechanisms for decision making, implementation review, conflict avoidance, dispute resolution, resource transfers, and so on will be important factors. Further, some institutions are more flexible and easy to adapt than others.

However, as the regimes become established and implementation processes begin, those involved with them are typically confronted with issues and processes of great complexity. The complexity of the *issue area* (the scientific issues and the social processes that have to be changed or addressed in the implementation process); *participation* (the number of participants and the diversity of types and interests); the *agreement*; and *institutional involvement* in the regimes can all be very great. In this context, centralized decision making cannot be sufficient to provide adequate adaptive management of the regimes. In this context, management theorists argue that institutions must combine a network of decentralized centers for identifying and responding to implementation problems and the need for adapting and developing the regime with systems for overall coordination.

In this context, processes of generating, disseminating, and responding to information can be critical. The significance for regime formation and development of knowledge about the environmental problem and appropriate responses to it is already well established in the literature (for example, Parson, 1993), as is the significance of the transnational scientific communities primarily involved in generating such knowledge (for example, Haas, 1992). Recent works on the role of implementation review processes are essentially emphasizing the importance of systems for generating, disseminating, and using knowledge about implementation (Parson, 1993).

One study within the IEC Project is a broad effort to identify long-term trends in the use and effectiveness of these mechanisms by comparing three dozen cases of flora and fauna biodiversity agreements. This study is the first application of a small data base of the systems for monitoring and reviewing performance in 50 international environmental agreements.

A second study compares "hard" (legally binding) and "soft" (nonbinding) agreements and explores how the specificity and legal status of agreements influence their effectiveness. In particular, it explores how review mechanisms can be important in soft law agreements (where they have seldom been studied), especially because they provide detailed information about needed adjustments to agreements; these adjustments tend to be easier to accomplish in more flexible soft law arrangements. The study consists of five cases (three soft law and two hard law): trade in hazardous chemicals and pesticides, food standards in the Codex Alimentarius, the FAO Undertaking on Plant and Genetic Resources, non-compliance within the Montreal Protocol, and enforcement of some GATT rules.

A third study examines in detail the procedures for exchanging data on pollutant emissions and acid deposition in Europe. Self-reported data is the common mode of exchanging information under international environmental agreements, but complete systems for reviewing and verifying implementation also require systems for checking the veracity and comparability of self-reported data. The European acid rain data system is one of the most successful in terms of volume of data transferred, and the Project is studying it to develop lessons that might help guide other systems, such as those for exchange of data related to climate change, to be more effective.

A fourth study investigates the Baltic Sea agreements and the Montreal Protocol on Substances that Deplete the Ozone Layer and identifies and explores the multiple ways and institutions through which implementation review processes actually develop in established and complex environmental regimes, how they interact, and how they can contribute to adaptive management of the overall regime. This study develops the case that implementation review appears to permeate the operation of complex regimes, and effectiveness seems to be linked with the ability to develop performance review within the committees and working groups as implementation issues become important and difficult and to link these closely with the revision or development of standards or exemptions. These can then be fed to the supreme review body directly if necessary rather than through a specific implementation committee.

Implementation Review and Adaptive Management in the Ozone Protection Regime: A Brief Illustration

The Montreal Protocol is widely regarded as one of the success stories in international environmental regimes, and as a model for tackling other global environmental problems. Certainly much has been achieved. Since the Montreal Protocol was agreed in 1987, commitments have progressively been strengthened. Industrialized countries have agreed to phase out consumption of the key ozone-depleting CFCs, halons, carbon tetrachloride, and methyl chloroform by January 1996. Moreover, most developing countries are also parties, and have agreed to phase out these chemicals by 2010. To help developing countries to meet their commitments, a Multilateral Fund (MLF) has been established to meet the "incremental costs" they incur in implementation. Industrialized countries have also agreed to phase out HCFCs over the next 30 years, and to freeze consumption of methyl bromide (MBr).

In Vienna in December 1995, these commitments were further developed. Industrialized countries agreed to reduce the cap on their HCFC consumption and to reduce the permitted "service tail" consumption between 2015 and 2030 to 0.5% of the 1990 calculated baseline year. They also agreed to cut their methyl bromide consumption by 25% by 2001 and by 50 % by 2005, with a total phaseout by 2010 (but with exemptions for preshipment and quarantine uses of MBr, which substantially reduces the stringency of this commitment). Significantly, for the first time developing countries also accepted commitments relating to these two ozone-depleting substances. They are to freeze consumption on MBr at 2015 levels after 2016 and to implement developed country phaseout commitments for HCFCs, but with a 10-year grace period (leading to a phaseout by 2040). These 1995 commitments are widely regarded as insufficiently stringent, and they are likely to be reviewed within the next two to three years.

In spite of this further development of commitments, the ozone regime has now reached a particularly challenging stage, not only in the further development of commitments but also in the effective implementation of existing ones. (For a review of the state of the ozone-depletion regime as it was in early 1995, and particularly its implementation issues, see Parson and Greene, 1995; for a review of the significance of developments, see Greene, forthcoming.) Serious concerns are emerging about reporting, compliance, loopholes, and "gray" or black market trading. Production and export of CFCs by developing countries such as India is expanding, raising disputes about whether these should be capped.

In relation to monitoring and implementation review, the ozone protection regime involves a wide range of reporting obligations, which have grown from requests to exchange information on the issue area of the Vienna Convention to reports of each party's production, imports, and exports of each controlled substance annually and for the relevant baseline year, which are required by the Montreal Protocol and subsequent amendments.

Implementation review is largely based on these national reports. Each of the Conference of the Parties (CoP) considers a report on implementation prepared by the Secretariat. This report includes tables of annual consumption and production data (aggregated according to groups of ozone-depleting substances, ODS; raw dissaggregated data reported to the Secretariat are confidential) of each party, and a comparison with the baseline year. There are also lists of ODS consumption per capita (to indicate Article 5 status), and data on reporting rates. Despite the best efforts of the Secretariat, implementation of reporting obligations has remained poor, and much of the discussion of implementation during CoP has focused on this problem. Until recently, the Secretariat's reports on performance have been considered en bloc by the CoP, without explicitly singling out poor performers, but the reports make their identity reasonably transparent.

Concerns about possible compliance problems stimulated the development of implementation review mechanisms and noncompliance procedures. An Implementation Committee (IC) was established to receive, consider, and report any submissions made by parties to the Secretariat in relation to noncompliance. The outlines of the noncompliance procedure were agreed upon at the 1990 London Conference, and the rules and procedures were adopted at the Copenhagen Meeting in 1992. The IC would consider written submissions from the parties concerned, would seek to resolve the problems, and would report to the next CoP. The Secretariat or the CoP can also refer issues relating to implementation to the IC.

The MLF has also established an important framework for reviewing the practices and plans of developing countries. Since Article 5 countries have a 10-year grace period on target dates, the MLF perhaps provides the only framework where developing countries current practices and plans come under systematic review. The MLF has, for example, been the forum where regime leaders could systematically raise questions about India's programs for the development of CFC production facilities. Moreover, it provided the framework in which China's plan to build an HCFC plant was discussed, stimulating awareness that developing countries as yet had no legal obligations relating to ultimately phasing out HCFCs and restricting methyl bromide consumption. These reviews take place within a context of grant applications and frequently contested criteria. Thus they are taken seriously by all concerned, but are prone to acrimony.

Similarly, the Technology and Economic Assessment Panel (TEAP) and its Technical Options Committees (TOCs) have played a key role in the reviewing implementation and identifying and responding to implementation problems, while also contributing substantially to the development of standards and commitments. For example, the Halons TOC has not only provided advice on the possibility of phasing out halons, but also played a major role in promoting and coordinating implementation of the phaseouts, reviewing the implementation of the halon bank distribution systems for essential uses, and assisting in many other implementation, management, and development tasks.

The European Union is also emerging as a key international player for the process of reviewing implementation in Europe. The EU is a party in its own right. It also plays a special role in the reporting process. It reports data to the Ozone Secretariat on ODS consumption, production, exports, and imports in EU countries as a whole. Moreover, although EU member states are obliged to send their own full reports to the Ozone Secretariat, several refuse to supply fully desegregated national data except in confidence to the EU Commission (where it is then aggregated with data from other member countries and forwarded to UNEP). Thus the EU plays a key role in monitoring and reviewing compliance among its member states.

In fact, the EU has established a system for thoroughly auditing the data supplied to it by examining the records of the main commercial producers, traders, and users (i.e., dealing directly with the sources of national data rather than working through national authorities). Partly because of a lack of confidence in the ability of Commission officials to maintain confidentiality, much of this task is contracted out to an auditing company. In relation to constructing baselines for newly controlled ODS involving new groups of producers and consumers (for example, methyl bromide), Commission officials have played the key role in checking the records and checking for discrepancies and double counting (reportedly there were such problems with methyl bromide).

The EU, through Commission officials and the relevant EU management committee of national officials, is also a key recipient of the reports from industries and others on possible noncompliance among competitors, and also on problems about the EU or Montreal Protocol regulations and procedures. In this framework several problems of possible black market trading (such as labeling new CFCs as "recycled") have recently been raised, and are now under consideration by the Open-Ended Working Group of the CoP.

In practice, industrial producers and users of controlled ODS have played an important role in monitoring and reviewing implementation. They have detailed knowledge of the operations of controls as they relate to them, and have a clear interest in reporting any problems or noncompliance that might effects their commercial competitiveness. In general, they have reported to the relevant national authorities, who can then raise the issue through diplomatic channels or through the mechanisms of the Montreal Protocol (and the EU).

Since 1992, the systems for reviewing implementation and responding to implementation and compliance problems have gradually become more active, and have started to work closely with each other. In the early 1990s a major activity was to address the continuing problems of poor compliance with reporting obligations. Initially, there was reportedly an element of competition between the Secretariat and the IC, but the working relationship improved in 1994. The Committee decided that many developing countries lacked the capacity to report and sought to mobilize assistance for them in coordination with the Multilateral Fund. Representatives of the Fund Secretariat and the implementing agencies began to attend IC meetings regularly as observers. Funding was provided to a number of developing states through the MLF implementing agencies. At its July 1994 meeting, the IC decided to focus on the roughly 40 states that had received some assistance, but were still not reporting. These countries were requested to account for themselves to the IC at its October meeting. Reporting rates improved substantially over the summer, and at the October meeting further promises to report soon were received.

However, in 1995 the implementation and compliance problems in Eastern Europe and the former Soviet Union posed a much more profound and potentially damaging challenge. The following paragraphs outline how these issues were dealt with in 1995 (for a more detailed discussion, see Greene, forthcoming).

Among the institutions of the Montreal Protocol in early 1995, it was the Secretariat and TEAP that had informally become most engaged with the question of how to respond to the emerging problem of noncompliance in the countries with economies in transition (CEIT). The Secretariat and the TEAP were already in regular contact with relevant Russian officials and experts on a range of issues. Moreover, the IC had already called Russia, the Ukraine, Belarus, and some East European countries to give reasons for not submitting data reports. Furthermore, the Montreal Protocol had an established noncompliance procedure, involving the Implementation Committee and an agreed range of possible responses to noncompliance.

However, any decision to initiate such machinery for noncompliance with basic phaseout commitments had to be handled with great care. There were few, if any, precedents for using such machinery in international environmental regimes. States can react very badly to being accused of noncompliance, and it was not at all clear how Russia and other states of the former Soviet Union would respond. It was important that compliance problems be addressed as cooperatively as possible, and that the process be initiated at an early stage – without waiting for unambiguous evidence of substantial noncompliance with the January 1996 phaseout commitment.

At the May 1995 session of the Open-Ended Working Group of Parties to the Montreal Protocol, Russia introduced a joint statement on behalf of itself, Belarus, Bulgaria, Poland, and the Ukraine, requesting a four-year extension of their phaseout schedules; an exemption from their contributions to the MLF; and international assistance with measures to phaseout ODS (statement by countries with economies in transition that are Parties to the Montreal Protocol – Belarus, Bulgaria, Poland, Russian Federation, and the Ukraine – circulated at 11th Meeting of the Open-Ended Working Group of Parties to the Montreal Protocol, May 1995). Then, on 26 May, the Russian Prime Minister, Mr Chernomyrdin, sent a letter to the Ozone Secretariat, addressed to the Parties of the Montreal Protocol. This letter stated that, although all possible efforts were being made, it was now inevitable that Russian compliance with the Protocol would not occur earlier than the year 2000. The main point of the letter was presumably to give notice to the Secretariat and Parties that Russia would therefore require a four-year extension. The Secretariat interpreted the letter as a formal initiation by Russia and the other four CEIT of noncompliance procedures. It thus decided that the letter, combined with the joint statement at the Open-Ended Working Group constituted a submission under paragraph 4 of the noncompliance procedures of the Montreal Protocol (Report of the Implementation Committee Under the Non-Compliance Procedure for the Montreal Protocol on the Work of its 10th Meeting, UNEP/ OzL.Pro/ ImpCom/10/4, 30 August 1995, para 31).

In this way, a key diplomatic problem of how to respond to imminent noncompliance in Russia and some other CEIT was resolved. It was clearly preferable for Russia to initiate the process. It is not clear if Prime Minister Chernomyrdin had envisaged this course of events when he had sent his letter. However, the Russian authorities accepted that the process could go ahead within this framework.

A key precedent had been established within the Montreal Protocol, and the regime's institutions set about the task of responding to the CEIT compliance problems. The matter was to be considered at the IC's 10th and 11th meetings in August 1995, by which time a draft report of the TEAP, "Ad-Hoc Working Group on CEIT Aspects," would be ready. In the meantime, efforts were made to alert countries of the former Soviet Union that had not yet become Parties to the Montreal Protocol (as revised at Copenhagen) that trade with them in CFCs, halons, and other ODSs from Russia or any other Party would be banned from the beginning of 1996 unless they met the conditions for being awarded a special exemption.

The IC was the key institution within which implementation problems in the relevant countries of Eastern Europe and the former Soviet Union were considered in detail and recommendations for responses to possible noncompliance were developed. This process took place during a number of IC meetings between August and December 1995. In addition to the representative of the country concerned, the 10 members of the IC [2], and the Ozone Secretariat, representatives of the MLF implementing agencies (World Bank, UNEP, UNDP, and UNIDO) and the MLF Secretariat were present, together with the co-chairs of the TEAP Ad-Hoc Working Group on compliance problems in CEIT. As is customary, the meeting was closed. No nongovernmental organizations (NGO) were represented (following an earlier request by one NGO to attend, it had been agreed that attendance at the IC by an NGO would normally be inappropriate and as a rule not permitted).

The approach adopted by the IC was constructive but rigorous. It recognized the difficulties these countries have experienced during their transition period. It was prepared, in principle, to consider the cases sympathetically, but not until the countries had fully complied with all of their data-reporting obligations and provided a detailed phaseout plan. This plan would then be examined in detail by the IC, with the advice of relevant TEAP experts, to identify the earliest feasible dates for phaseout of each gas in each sector and to establish intermediate targets and procedures to review progress. Although Russia and the other CEIT are not eligible to receive any assistance from the MLF (which is available only to developing states parties), it was informally noted that assistance from the Global Environmental Fund (GEF) might be available to Russia and other CEIT, but only if they cooperated fully with a compliance plan of the IC. The countries accepted this approach. They agreed to provide the outstanding data in the required format, but asked for assistance in collating the data from different sources. They also agreed to provide detailed phaseout plans.

By the December 1995 Meeting of the Parties, relevant production and consumption data had been provided, but Russia had not provided sufficiently detailed plans and there were ambiguities in the plans of some of the other states concerned. The implementation committee decided to recommend to the Meeting of the Parties that Russia be asked to resubmit further information on its phaseout program at a special meeting of the IC in February 1996. If this was found to be satisfactory, the GEF would be asked to provide funding assistance. Russia's progress toward compliance would subsequently be regularly reviewed. Until it came into compliance, the IC recommended that trade in recycled or recovered CFCs would be banned between Russia and non-CEIT industrial countries.

Russia found these recommendations hard to accept, particularly the trade restrictions. For a tense period, it appeared that the Russian government would reject the entire procedure, and call for a vote at the Meeting of the Parties (which it would be sure to lose, but which might set the scene for Russia to declare it had suspended participation in the regime). However, the Ukraine and Belarus found similar restrictions acceptable, and Russia decided to accept the procedure and most of the IC's recommendations, while opposing the trade restrictions. The Meeting of the Parties made the recommendations more stringent, deciding to ban Russian trade in CFCs with developing countries as well. The recommendations were accepted by a technical consensus, with Russian objections being registered in the report of the meeting.

Significantly, the TEAP ad hoc working group subsequently was assigned the task of advising on efficient ways of revising and implementing the phaseout plans in the Ukraine, Russia, and Belarus.

The Montreal Protocol is an inspiring example of a flexible and adaptive regime. Although it would be a mistake to adopt it directly as a model for other environmental regimes (see, for example, Greene, 1995), there is much to be learned from the consistent inventiveness and combination of flexibility and rigour it has displayed. It is not yet clear how well the regime will deal with the implementation problems that have emerged now that phaseouts must implemented. However, it has already established important precedents.

The development process has taken place in the context of constant implementation review, in the sense that emerging implementation problems and experiences have regularly been raised and considered by the Secretariat, TEAPs, MLF Executive Committee, Implementing Agencies, IC, and Meeting of the Parties. Those familiar with the wide range of activities associated with the implementation and development of the regime must be struck by the sheer density of processes and institutions. The institutions of the regime engage a wide range of different types of actors involved with implementing and reviewing the regime, including industrial users and consumers, technical experts, regulators, and NGOs as well as international institutions and government officials.

The Montreal Protocol noncompliance procedure and the standing Implementation Committee are unique among environmental regimes, and have recently demonstrated their value. Some lessons learned so far include the value of having a standing committee to deal with noncompliance issues and established procedures combined with a Secretariat with a remit to promote compliance and raise concerns; the importance of the Meeting of the Parties consistently referring possible noncompliance issues to the IC; the advantages of "constructive" "conflict avoidance" procedures for dealing with noncompliance over the dispute resolution mechanisms, which are never used.

The TEAP and its Technical Options Committees play a key role in implementation review, regime development, and decision making, as well as in the implementation processes themselves. The MLF Executive Committee and the implementing agencies have played a significant role in reviewing operations and identifying problems that need to be addressed. They are also developing more effective project implementation review procedures. The EU is also emerging as a key international focal point for reviewing implementation in Europe. The combination of the IC, TEAPs, MLF/Implementing Agencies, and GEF was critical for the success of the noncompliance procedure. This is particularly illustrated by the role of TEAP advisers and implementing agency observers at IC meetings and also in response to noncompliance.

Concluding Remarks

The IEC Project at IIASA focuses on what happens after agreements have been reached: What factors determine whether and how they are implemented and developed, and when do they make a difference? The answers are important for policy makers, as well as researchers, because they can be used in efforts to design more effective agreements and implementation policies. The Project addresses several clusters of questions about what promotes implementation of international environmental agreements and how to make environmental regimes more effective.

In addition to contributing to the understanding of the implementation and effectiveness of a number of important environmental agreements in the past, the Project aims at contributing to the development and implementation of environmental commitments in the future. Lessons have been learned about the significance and role of various types of institutions, rules, and mechanisms, and particularly about the ways in which international institutions can connect with domestic implementation processes.

In this context, researchers in the IEC Project have also been seeking to apply their findings to future policy, and have been particularly active in this respect in relation to the development of the Montreal Protocol and the climate change and biodiversity conventions. Moreover, the Project's research team is tracking the dynamic situation of international environmental agreements in the former Soviet Union, and periodically publishing briefings for a broad audience.

Notes

[1] This paper draws on the work of the Project's entire research team. Currently, the IEC research team includes scholars from Europe, Russia, and North America and spans several disciplines, primarily from the social sciences and law. Most project scientists are involved on a part-time basis, and regularly working for short periods at IIASA. David Victor is the Project co-leader in residence at IIASA, and Eugene B. Skolnikoff, Department of Political Science, MIT, USA, serves as its nonresident co-leader. Among the principal investigators and participants, most of whom spend extended periods of time at IIASA, are the following: Owen Greene and Julian Salt, Department of Peace Studies, University of Bradford, UK; Steinar Andresen, Olav Schram Stokke, Jon Birger Skjaerseth, and Jorgen Wettestad, Fridtjof Nansen Institute, Norway; Helmut Breitmeier, IIASA; Juan Carlos di Primio, Karlsruhe, Germany; Ronnie Hjorth, Department of Political Science, Linkoping University, Sweden; Vladimir Kotov, School of Business Management, Academy of Transport, Russia; John Lanchbery, Verification Technology Information Centre, London, UK; Marc Levy, Woodrow Wilson School, Princeton University, USA; Elena Nikitina and Alexei Roginko, Institute of World Economy and International Relations, Russian Academy of Sciences; Edward Parson, Harvard University, USA; Kal Raustiala, Department of Politics, Brandeis University, USA; Oran Young, Dartmouth College, USA; and Michael Zurn, University of Bremen, Germany. An advisory committee also contributes by periodically reviewing progress and providing advice. This committee consists of Abram Chayes, Harvard Law School, USA; Gueorgui S. Golitsyn, Director, Institute of Atmospheric Physics, Russian Academy of Sciences, Moscow; Peter Sand, former Legal Adviser, World Bank, Germany; and Arild Underdal, University of Oslo, Norway.

[2] At that time, the 10 countries elected to serve on the IC were Austria (chair), Bulgaria, Burkina Faso, Chile, Jordan, the Netherlands, Peru, the Russian Federation, the United Republic of Tanzania, and Slovenia.

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Methods for Decision Support for Global Issues

Presented by

Jaap Wessels
Project Leader, Methodology of Decision Analysis

Methods for Decision Support for Global Issues

Jaap Wessels

Introduction

Everyday life largely consists of decision making. We decide what, when, and where to eat; where to go; which route to take; and which means of transportation to use. This type of decision making is an interesting topic for scientific research, but it is not the topic of this paper. In this paper I discuss the types of decisions made in more formal settings, in other words, *institutional decision making*. Although the discussion is restricted, it still allows for the examination of a broad range of topics – such as decision making in local enterprises on scheduling operations or decision making in the UN Security Council on the cultural and economic blockade of a member country. The paper focuses primarily on issues in the public domain that have an international or global impact. Most of the observations are relevant to the wider area of institutional decision making. Typical examples include treaty negotiations on acid rain abatement between several governments in a region, the selection of actions to comply with CO_2 emission limits imposed by an international agreement, and negotiations on water rights and purification obligations between countries sharing one river basin.

All such decisions are taken in a more or less formal setting, which should guarantee that different aspects are taken into account. As a consequence, decisions result from rather complex decision processes in which different groups may take part. Such features may be most evident in public domain decisions with international or global impact; however, the same features can be recognized in many public domain decision-making processes on a national or local scale. Business decisions often have similar features, particularly if they are of a tactical or strategic nature. Usually, only operational business decisions are taken by one planner, provided he or she remains within a given range of actions and can defend his or her choice afterward.

Since World War II, an ever-increasing number of methods have been designed for analyzing decision situations and for supporting decision processes. This development represents the *scientific approach* to decision making. Such methods have been extremely successful in many cases, but there are also many cases where such methods contributed little or nothing. The scientific approach has strong adherents, but it also has its opponents who question the relevance of systematically developed methods and stress the importance of negotiating skills, diplomatic talents or gifts, personality, and so on.

We can roughly distinguish between the *scientific* approach and the *artistic* approach to institutional decision making. The *artistic* approach depends on creativity and intuition, and is based on the practioner's experiences and abilities rather than on his or her knowledge. It also integrates different aspects, it is subjective. The *scientific* approach depends on systems, rationality, and consistency, and is based on objective knowledge rather than on experience and personal abilities. Adherents of each approach can boast of success stories and identify failures of the other approach. The artistic proponents argue that the scientific approach will never be able to integrate all aspects of real decision problems into one comprehensive view, which can only be obtained and explored by experienced and talented individuals. The scientific side argues that the scientific approach guarantees an objective view of the advantages and disadvantages of possible decisions. Both arguments are legitimate.

From an academic point of view, it would be ideal if decision making could rely completely on the scientific approach. However, this assumption is clearly not realistic for two reasons.

First, it is illusory to believe that all aspects of decision making are really open to a scientific approach. For instance, the very complicated aspect of interpersonal relationships have a substantial impact on decision making. A great deal of research has been conducted on interpersonal relationships in small groups and negotiating bodies. However, although this type of research provides insights into the relationships between decision makers, it does not provide information of the systematic methods for treating the interpersonal relationships of decision makers. Scientific knowledge on this aspect mainly leads to guidelines. In straightforward decision processes, we encounter features which are difficult to grasp, even when background knowledge is available. For instance, in production planning, producers would like to understand the demand processes. However, in a number of cases, the information available on such processes is limited. In this situation the instincts of an experienced planner are frequently very helpful.

The second reason is that most methods used in the scientific approach are essentially based on only one aspect of the problem; the other aspects are poorly incorporated. This phenomenon is discussed later in the paper.

Because of the intensive research activities on decision-making-related issues, one would expect that the scientific approach would generate more effective methods in the future. Nevertheless, one should not assume that these activities will lead to a situation in which the artistic arguments no longer hold. Therefore, we may be required to accept the limitations of the scientific approach. Since the artistic approach also has its limitations, it would be wise to accept the idea that the two approaches do not necessarily exclude each other but rather complement each other. As a consequence, decision-support methodology should be developed to allow for constructive interplay between *scientific* and *artistic* activities within decision processes. Accepting that the scientific approach cannot solve the decision problems completely implies acceptance of the essential role of the ability of the decision makers involved. This acceptance implies that the scientific approach no longer aims at providing a full solution (which may be amended somewhat by the negotiators or decision makers), but aims at providing the persons and groups involved with information and insights that increase their ability.

These observations play an essential role in the work done at IIASA in the area of methodology for decision support. In this paper, I provide an overview of the methods generated by the scientific approach, show why integration of several aspects is difficult, and identify opportunities for future directions. Such a topic is appropriate for a systems analysis institute, because the most pregnant feature of systems analysis is that it tries to provide an integrated assessment of different aspects of a problem.

The next section outlines the main aspects of decision problems. The subsequent section, Section 2, gives an overview of methods for decision analysis or decision support that are essentially based on one of those aspects. Section 3 attempts to develop methods based on at least two aspects in an integrated way. In Section 4, I discuss how experiences should be used in future work, and Section 5 describes some experiences of IIASA and related institutes.

Aspects of Decision Problems

Institutional decision problems have many aspects, which can be grouped in different ways. The way of grouping, to some extent, reveals the point of view of the author. My background is in hard science, which explains the bias in my way of grouping these aspects.

Information is the first aspect encountered when one must make a decision. Quite often there are large amounts of data which are related to the decision situation. For instance, a water pollution problem may require data on rainfall, demographic trends, industrial water use and pollution emissions, agricultural and household activities, biological dynamics, and geography. In cases with large amounts of data, it is very helpful if the data are presented in a concise and well-ordered way.

However, apart from raw data, one must deal with mechanisms that compare different features. Hence another basic aspect consists of *the underlying physical or economic processes.* In the case of a water pollution problem, these processes include water flows, dispersion processes of pollutants, chemical and biological reactions in the water, and pollution as a function of economic activity. Indeed, clear models for underlying physical or economic processes can help clarify the effects of some measures.

Knowledge of these aspects might help to understand the real issue, which is the aspect of *the relation between decisions and consequences.* In this example of water pollution, several types of consequences can be identified that depend heavily on the final decisions: for example, water quality and marine life may depend heavily on decisions on purification investments and constraints for industrial or agricultural activities in sensitive areas.

These are the three basic aspects of the decision situation, but attention cannot be restricted only to these features that are influenced by the decisions, because frequently the ways in which decisions are prepared and made must be taken into account. Quite often, an essential aspect of the problem is *the decision-making process.* Frequently several bodies are involved in the decision-making process; these include local, regional, and national authorities, industries, agricultural groups, neighboring countries, and intergovernmental bodies. The decisions do not usually result in a single action, but consist of large interrelated sets of actions that are structured to deal with time constraints and primary responsibilities.

This way of grouping various aspects of decision making reveals that each aspect may be taken as a very reasonable starting point for supporting the decision process. In the next section I demonstrate that practically all established methods for decision support and decision analysis are essentially based on only one of these aspects (and sometimes only a part of one aspect) and that the possibilities of integrating other aspects are limited.

Decision Support Approaches Based on a Single Aspect

In this section, specific approaches are applied to a particular aspect. There are at least two dominant aspects present in most institutional decision problems. Of course, there are some decision problems for which one aspect is dominant and such cases provide the success stories for protagonists of a particular approach. In fact, in cases where at least two aspects are dominant, single-aspect approaches can also be helpful. If carefully applied, they help to decrease complexity. However, they may also underestimate the importance of less explicitly treated aspects. Approaches based on each aspect are indicated below.

Information: Management Information Systems and Geographic Information Systems

Typically, approaches based on the information aspect try to provide a framework in which large amounts of data may be stored and processed in a way that, upon request, the user may obtain different views in an easy-to-understand presentation. Essential in such approaches is the flexibility with which the user may select which views he or she would like to see. There are several other similar approaches; they are usually dedicated to a particular application.

Such approaches are strong in providing insights into the current situation and/or historic developments; however, they are relatively weak in showing consequences of possible decisions. Usually, these approaches do not provide any relation to the decision-making process.

The underlying processes: Scenario analysis based on a model of the underlying processes

There are practically no generally applicable tools for this approach. This is because the methods for the model evaluation may differ strongly and – even within a single application – may need to be adapted to different scenarios. Evaluation methods may stem from such diverse areas as discrete event stimulation, queuing theory, and differential equations. The modeling approach is determined largely by the evaluation method; therefore, the tools are usually oriented toward the evaluation method rather than to the decision situation. For most evaluation methods, computer packages are available. These packages are frequently tailored for a particular application area, although this is not always explicitly stated. There has been strong development in advanced evaluation tools based on the analysis of complex mathematical models. Such tools have been developed particularly for business and infrastructure applications. Typical examples are the design of communication networks, distribution systems, and production sites. Despite this development, many applications are still based on simple evaluations of crude and informal models. This is particularly the case for strategic decisions in business, as well as in the public area. For technical reasons, the models are often less detailed than the information would permit. Usually, there are no good tools for deriving the models from the available information. This step is primarily based on the capabilities of the modeler. It is usually difficult to construct a good scenario; and it is particularly difficult to make clear that an available scenario is, by and large, the best one possible. However, there is a favorable link with the decision-making process in the sense that scenario analysis is well suited for a stepwise decision-making process in which in each step decision makers provide the ingredients for a new scenario and receive the evaluation results in return.

The relation between decisions and consequences: Mathematical Programming, Multi-criteria Decision Analysis, and Game-theoretic Modeling and Analysis

All approaches based on this aspect take as a starting point that a set of feasible decisions can be identified and that, for each feasible decision, the consequences can be summarized in a standard format. For the Mathematical Programming approach, the starting point is further specified by requiring that decisions are represented by vectors, i.e., each decision is represented in a finite sequence of real-valued or integer-valued numbers. Further it is required that feasibility is validated by checking a set of mathematical relations (for instance, linear inequalities) for the numbers representing the decision. The interpretation is that decisions satisfying these relations have acceptable consequences; infeasibility is implied if at least one of the consequences is unacceptable. Usually, each mathematical relation represents one type of consequence.

In addition, a real value is given for each decision; this value represents the desirability of the decision. The desirability value is obtained by applying some mathematical function to the numbers that represent the decision. Frequently, this function also represents one of the consequences or even some combination of consequences.

The basic form of Mathematical Programming is linear programming, with linear equalities and inequalities (linear functions of the decision numbers) for the feasibility constraints and a linear function for the desirability indicator or optimality criterion. Within the same framework, several variants of the linear programming model have been developed, i.e., nonlinear programming, (mixed) integer programming, and stochastic programming.

Multi-criteria Decision Analysis is an offshoot of Mathematical Programming. It differs from the latter by having more than one desirability indicator.

Game-Theoretic Modeling and Analysis differs from Mathematical Programming in that it involves more than one party, and each party determines its own part of the decision vector.

The Mathematical Programming approach has generated a large number of software tools – primarily tools for finding solutions, but also tools for constructing the models. The first solution techniques for linear programming date back to the late 1940s (cf. Dantzig, 1963), but progress is being made today by introducing new techniques and adapting older ones (cf. Bixby, 1994).

The Mathematical Programming approach has become so successful that, for many people, Mathematical Programming and Decision Support have become identical; they have translated the concept of Mathematical Programming into a paradigm for decision making. This poses a real danger, since it forces decision makers to look at situations with a predisposed view.

It is not easy to relate these approaches to other aspects. This is partly due to the fact that applications require highly aggregated views and partly due to the inherent rigid view about the decision-making process.

These three approaches are based on modeling the relations between decisions and consequences. However, some approaches avoid explicit modeling and replace it by learning from examples. The best known approach in this style is Neural Nets. The Neural Net Approach exploits the fact that, in many decision situations, it is very clear afterward which decision should have been taken (for example, stock market decisions), whereas the modeling may be very complicated. By adapting the parameters of a black box in such a way that the right decisions are prescribed in the examples, one also hopes to obtain good decisions in similar new situations.

The decision-making process: Decision Trees, Group Decision Support, Negotiation Facilitating, Multi-attribute Utility Theory, Expert Systems, Neural Nets, and Analytic Hierarchy Processes

The fourth aspect has several approaches; each approach aims at only part of the aspect. This feature indicates that *the decision-making process* aspect is not really one aspect, but comprises several minor aspects.

Expert Systems and Neural Nets aim at mimicking the decision behavior of an expert; Expert Systems try to imitate the user's way of reasoning; and Neural Nets imitate the effective behavior of the expert without trying to understand the arguments behind it. Such approaches are primarily relevant for routine decisions. Nevertheless, in nonroutine decision making such approaches may sometimes be used for specific parts of the real decision process.

The other approaches concentrate on one or more minor parts of the decision-making process. Decision Trees, the oldest approach in this set, deals with the structuring of decisions (first decide whether you want to build a new factory; if yes, then decide where). Group Decision Support focuses on the fact that many decisions are essentially taken by groups rather than by individuals. Negotiating Facilitating accepts that decisions are frequently based on negotiations between parties with different interests (cf. Raiffa, 1982). Multi-attribute Utility Theory deals with the feature of complex preference structures (cf. Keeney, 1975; Keeney and Raiffa, 1976). Analytic Hierarchy Processes provides an approach dealing with a few of these minor aspects. Some of the approaches mentioned in this category leave at least some space for some integration of one of the other aspects.

All of these approaches can boast of impressive success stories. One reason for this is that the approaches have been initiated and developed by extremely talented people; sometimes the successes tell more about the capabilities of the initiator than about the quality of the approach. The second reason for their success is that each approach is appropriate for a particular class of situations. The third reason is that it is not necessarily bad to concentrate support on one aspect. If other relevant aspects are not forgotten, it can be helpful to have some method for treating one particular aspect, making the whole decision situation clearer in that way. However, this requires an open mind. Teaching separate approaches limits the practitioner's opportunities for observing the real decision problem. The Mathematical Programming approach has induced people to believe that real decision problems are essentially Mathematical Programming problems which can be discovered by removing a layer of dust. The same attitude can be found with people trained in other approaches. So the quality of an approach is determined not by the successes of the initiators, but rather by the failures of their followers.

Integrated Approaches Toward Decision Support

The previous section shows that many approaches toward decision support and decision analysis are essentially based on only one aspect or even a minor aspect of the decision situation. Such approaches can be both helpful and dangerous.

The main reason for introducing approaches with only one aspect is based on the fact that one aspect confronts us already with a complex problem. Most of the discussions in the literature are devoted to extending single-aspect approaches to more complicated and more realistic problems. And although much has been achieved, there is still much more to be accomplished. Therefore, it might seem strange to embark on attempts at integrating different aspects. In fact, at this time it is commonly accepted that such attempts may not lead to widely applicable approaches. However, it is worth exploring the possibilities of and experiences with integrated approaches, even in specific application areas.

In this section I describe some attempts that seem to have wide relevance. However, many more attempts have been made in particular cases.

The most successful efforts try to integrate the following aspects: *the underlying processes* and *the relation between decisions and consequences*. The most straightforward way of achieving such an integration is by incorporating decisions into a process model in a way that the consequences become clear. Typical approaches based on this idea are Optimal Control and Markov Decision Processes. Such approaches integrate ideas of Scenario Analysis and Mathematical Programming. These attempts have proved to be very stimulating in the mathematical sciences; in practice, they have proved to be effective in restricted sets of applications, mostly operational applications.

There are also attempts to enhance scenario-based simulation experiments with diagnostic tools in a way that the search for good scenarios can be supported effectively. In this direction, the mathematical developments are quite exciting, the practical results are incidental but promising (cf., for instance, Ermoliev *et al.*, 1992). Other attempts try to enhance scenario analysis with policy search methods that exploit rule-based techniques. The possibilities seem to depend strongly on the particular cases (cf., for instance, Boers *et al.*, 1992).

Still other attempts aim at integrating *information* and *the underlying processes*. Information systems store data in a well-structured way based on some sort of data model. Attempts to link such information systems directly with process models for scenario analysis are usually not very successful, since such process models tend to be based on concepts that are not in line with the data models. The main reason for this feature is that process models are conceived from the point of view of some evaluation method. A way to overcome this difficulty is by trying to formulate process models from the point of view of reality as a direct description of the real process and to develop evaluation methods for such process models. Actually, this situation implies that the true and recognizable description of real processes is considered more important than efficient and sophisticated evaluation. Such new types of process models are themselves an extended type of information system and may also be used for building a more traditional process model if necessary.

Well-known techniques for making close-to-reality process models are provided by Petri Nets and by Process Algebra. Approaches and tools based on these techniques have been developed. Results are promising in particular application areas (cf., for instance, Van der Aalst, 1992; Wessels, 1993).

In conclusion, development of methods that integrate different aspects is scientifically challenging and may introduce important results in the near future. However, we must accept that fully integrated and generally applicable approaches will not be available in the foreseeable or distant future.

What's Next?

It is safe to conclude that it is not realistic to rely on the availability of approaches that integrate all aspects of decision problems. Some attempts have tried to integrate two aspects, and these attempts have led to optimism about promising results in particular application areas. These attempts rely strongly on particular techniques that considerably restrict the application areas.

It was concluded in Section 2 that single-aspect approaches may be very helpful, but also possess the inherent danger of shaping the opinions of the users in a very rigid and biased way. There are at least two ways to deal with these constraints. First, attempts should be made to continue to develop approaches that integrate at least two aspects. Such attempts will be valuable from the point of view of research, and probably generate good approaches in certain areas of application. In the extended long run, concepts may be broadened to additional areas of application. Second, it is important to develop a plan for attacking decision problems in a way that variants of existing approaches can be used profitably, avoiding the danger of single-mindedness.

The latter method actually consists of two types of activities. In the *first* type, a research style should be developed that focuses on the decision problem and reduces the existing approaches to simple techniques, which can be used if there appears to be a need. This style would require a method of describing decision problems without any reference to the existing approaches, and it also would require a method of treating the problem with new and existing techniques. A good example of this alternative style, which shifts attention from the techniques to the decision process with all its intangible inputs and outputs, is the Shinayakana System Approach (cf. Sawaragi and Nakamori, 1991).

In the *second* type, variants of new techniques must be developed in a way to fit into the proposed style. This method requires that off-the-shelf techniques are combined with other ready-made and tailor-made techniques. Approaches are applied as techniques rather than as (implicit) paradigms. This approach is quite a change from existing techniques.

Of course, these ideas are not completely new. Actually, most of the work conducted at IIASA in the area of decision support and decision analysis fits well into this line.

Experiences

The research project Methodology of Decision Analysis at IIASA centers its activities on decision support based on optimization and multi-criteria analysis. Consequently, the emphasis has been on *the relation between decisions and consequences* aspect. Over the years negotiations (cf., for instance, Spector *et al.*, 1994; and for the use of formal methods, *Theory and Decision*, 1993) and preference structures (cf. Keeney, 1975; Keeney and Raiffa, 1976) have been important methodological topics at IIASA. Concentrating on decision support based on optimization and multi-criteria analysis, we have recently shifted attention from a single-aspect approach to developing off-the-shelf tools that can be applied in a problem-concentrated approach and that do not try to control the situation. The tool-development activities were executed in close cooperation with a large group of Polish colleagues coordinated by A.P. Wierzbicki. First discussions on the change in emphasis were held at an IIASA workshop in Serock, Poland in 1991 (cf. Wessels and Wierzbicki, 1993). These activities were accompanied by practical involvement in decision support development within and outside IIASA. The experiences with applications and with tool development will be described in a book, which is under preparation and which will contain contributions from tool developers as well as from modelers.

At IIASA there is a long tradition of using linear programming (Dantzig, 1963). However in the early 1990s it became evident that application of linear programming to actual complex problems did not proceed as naturally and smoothly as might be expected from an already classical technique, which was still improving considerably (cf. Bixby, 1994). There appeared to be two reasons for this phenomenon. First, it seemed that in large and complex problems there was a mixture of scenario analysis and optimization (i.e., the essential approach could only be scenario analysis; but within those complicated scenarios there was room for optimization, for example, to account for cost-optimal behavior within given scenarios). Second, it appeared that the standard linear-programming software could not easily be built into the relatively complicated procedure in which the linear programming was not a dominant part. So, in such applications, the best software available was based on a restrictive paradigm about decision making.

These observations prompted us to rebuild the linear-programming solvers in such a way that they could be used as flexible built-in modules. Three such modules are now available, each based on a different optimization technique (cf. Gondzio and Makowski, 1995; Makowski and Sosnowski, 1989; Makowski, 1994a). The experiences with the new solvers have been very positive. For instance, HYBRID, which applies a particular implementation of the proximal multiplier method, is built into a new version of the RAINS software package (Alcamo *et al.*, 1990). HOPDM, which applies an interior point method, is used for land-use and energy problems (cf. Antoine *et al.*, submitted; Antoine *et al.*, 1996; Nakićenović *et al.*, 1993). The classical simplex-method is used in a subprocedure for a water quality problem (cf. Makowski *et al.*, submitted). It appears to be important to possess a variety of exchangeable solvers, since each has its own advantages and disadvantages. All solvers can be combined with other tools, for example, a tool for handling data (cf. Makowski, 1994b; Makowski and Savelsbergh, 1993) or a tool for specification and analysis of user preferences (cf. Granat and Makowski, 1995). Similar concepts have been applied to nonlinear and combinatorial optimization problems.

Another feature, which was made possible in this way, was the analysis of decisions against several criteria. Since it is usually not possible to find decisions that are simultaneously optimal against all relevant criteria, one has to accept a compromise. In some cases such a compromise may be found by applying one overall criterion, but usually it is better to apply an interactive approach controlled by the user. (For such approaches see Sawaragi *et al.*, 1985; Lewandowski and Wierzbicki, 1989; Wessels and Wierzbicki, 1993. For tools see Wessels and Wierzbicki, 1993; Matsuoka *et al.*, 1995; Granat and Makowski. For applications see Nakayama, 1993; Antoine *et al.*, submitted; Antoine *et al.*, 1996; Makowski *et al.*, submitted.) These approaches assume the existence of clear and separate criteria. However, not all policy problems possess such criteria or they combine hard criteria, which are directly related to physical or economic processes, with soft criteria, which are directly related to social and political processes. Pöyhönen (1994) has shown, in a Peccei-Award-winning report, that evaluation procedures can be constructed that guarantee a balanced influence of hard and soft preferences. Indeed, in such a stepwise procedure, modular tools appear to be helpful.

Several environmental problems are even more complex with many interacting factors. For such problems, NIES is involved in developing models like the AIM Model and the Framework Model (cf. AIM, 1994; Matsuoka *et al.*, 1995; Morita *et al.*, 1995; Kainuma *et al.*, 1995). By cooperating with our Japanese colleagues, IIASA has contributed significantly to the environmental modeling processes as well as to developing decision support methodology.

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Population and Environment: Global and Local Perspectives*

Presented by

Wolfgang Lutz

Project Leader, Population

*Within the panel discussion on "Trilemma."

Population and Environment: Global and Local Perspectives*

Wolfgang Lutz

This presentation covers three aspects currently under study by IIASA's Population Program.

1. **World Population Projections**: New 1996 world population projections have been produced by the Population Project. In addition to giving a most likely path and alternative scenarios, the results include first-ever probabilistic world population projections. These allow users to attach certain probabilities to alternative future paths of population growth. Special emphasis is also placed on future population aging in low-fertility countries.

2. **Population and Global Warming**: A large set of data on energy use by type of energy are connected to alternative population scenarios to estimate future CO_2 emissions. A new aspect of this kind of analysis is the assignment of the demographic cause of increased emissions not only to population growth but also to the number of households. Calculations show that if households are taken as the primary emitting unit, then the demographic changes of households in industrialized countries have a far greater impact on emissions than the demographic changes of individuals. These new calculations will be detailed in an IIASA book currently under preparation.

3. **Population–Development–Environment (PDE) Case Studies**: In-depth studies of complex population–environment interactions can meaningfully be done only at the regional level because conditions are so different in different parts of the world. The IIASA PDE model approach has so far been applied to the demographic trends that have been observed on the island of Mauritius and the Mexican Yucatán peninsula.

* Within the panel discussion on "Trilemma."

Modeling the Driving Forces of Land-Use and Land-Cover Change

Presented by

Günther Fischer

Project Leader, Modeling Land-Use and Land-Cover Changes in Europe and Northern Asia

Modeling the Driving Forces of Land-Use and Land-Cover Change: The IIASA Land-Use Change Project

Günther Fischer

Introduction

In 1995, the Modeling Land-Use and Land-Cover Changes in Europe and Northern Asia Project (LUC) was established at IIASA. The objective of the Project is to analyze spatial characteristics, temporal dynamics, and environmental consequences of land-use and land-cover changes that have occurred in Europe and Northern Asia over the period 1900 to 1990 as a result of a range of socioeconomic and biophysical driving forces. The analysis will be used to project plausible future changes in land use and land cover for the period 1990 to 2050 under different demographic, economic, technological, social, and political development assumptions. The study region, Europe and Northern Asia, has been selected because of its diverse social, economic, and political organizations, the rapid changes it has experienced in recent history, and the significance of these changes for current and future land-use and land-cover change.

Land-cover change is driven by a multitude of processes. Natural processes, such as vegetation dynamics, alter land cover and are due to natural changes in climate and soils, or due to fires. However, land-cover changes driven by anthropogenic forcing are currently the most important and most rapid of all changes (Turner *et al.*, 1990). Therefore, any sound effort to project the future state of land cover must consider the determinants of human requirements and activities (e.g., demand for land-based products such as food, fiber, and fuel, or use of land for recreation).

In the past, major land-cover conversions have occurred as a consequence of deforestation to acquire land for crop and livestock production; removal of wood for fuel and timber; alteration of wetlands; development of infrastructure; industrial and residential construction; and mineral extraction (Turner *et al.*, 1993). These human-induced conversions of land cover, particularly during the last two centuries, have resulted in a net release of carbon dioxide to the atmosphere, changes in the characteristics of land surfaces (e.g., albedo and roughness), and decreased biodiversity.

Subtler processes, termed land-cover modifications, affect the character of the land cover without changing its overall classification (Turner *et al.*, 1993). Although land-cover modifications may have a small effect on local scales, their aggregate impact may be considerable (Houghton, 1991). For example, use of fertilizers locally has no significance for atmospheric concentrations of greenhouse gases. However, when nitrogen fertilizer is applied frequently in many locations, it can make a significant contribution to emissions of nitrous oxide globally.

The Welfare Approach

The implementation of a comprehensive land-use change model poses a number of methodological challenges. These include the complexity of the issues involved and the large number of interacting agents; the nonlinear interactions between various factors such as markets; the supply of and the demand for land-based commodities and resources; the importance of intertemporal aspects; the intricacy of biophysical feedbacks; and the essential role of uncertainty in the overall evaluation of strategies.

The interaction mechanisms between biophysical cycles and economic processes have mainly been studied in dynamic simulation models that follow recursive chains of causation, where past and present events determine what will happen tomorrow. Not surprisingly, many of these studies have led to dramatic predictions, basically because the agents (or actors), whose behavior is described within the model, are assumed to be unable to anticipate the future. By contrast, in microeconomics it is usually assumed that agents do have the capacity to make informed predictions and plans that avoid the probability of disaster in the future. However, even complete information and rational individual choices are not always sufficient to avoid disaster. The coordination mechanisms that prevail among economic agents often tend to be of decisive importance.

It is relatively easy to project which conditions will produce doomsday in a long-term model; a simple trend extrapolation will usually do. Finding an ideal solution that will prevent doomsday from occurring is obviously more difficult, and also more challenging. By design, the analysis of intertemporal welfare programs provides ideal (i.e., best case) trajectories of demand, supply, and resource use and of land allocation. Then, no-action or business-as-usual scenarios are specified that start from present-day conditions and serve to highlight some of the threats that the system is currently facing. We call this *bracketing* of the future between ideal and doomsday scenarios the *welfare approach.*

The formulation of a welfare program is the conceptual centerpiece of the LUC modeling activity. The welfare program is written as an optimization problem that maximizes the weighted sum of the utilities of the participants, i.e., the consumers. There are four types of constraints to be specified in a welfare program:

1. The utility constraint specifies in a recursive way how the utility of a given group of consumers in period t depends on consumption in that period as well as on the group's utility in the next period. This is a characterization of the preferences of every group.
2. The transformation constraints describe the net supplies in period t and resources in period $t+1$ that are feasible at the given level of resources in period t. These constraints provide a characterization of the technology of the economy, i.e., of its capacity to produce new commodities with current commodities, labor, and natural resources. Resource dynamics are part of this set of constraints. For example, if some trees in a given stock of trees are cut and sold, this cutting, together with replanting, will determine the stock of trees in the next period. If there is no replanting and the cleared land is allocated to agriculture, there will be a change in the stocks of land: a reduction in the area under forest and an increase in a particular type of agricultural land. In the LUC Project, a substantial part of the data collection and analysis is being devoted to adequately specifying the transformation constraints describing the technology and resource dynamics that govern the main land-based sectors of the economy – agriculture and forestry.
3. The commodity balance constraint ensures that the demand by consumers does not exceed the net supply that is feasible in the transformation constraint and from trading. This balance is determined for every commodity.
4. The stock consistency constraint makes certain that the level of resources used in period $t+1$ should not exceed the level carried over from period t. The stock consistency constraint must hold for every resource.

A welfare program may look like a central plan that would be implemented in a command economy. Clearly, this is not our objective. On the contrary, a main advantage of the welfare approach is that, under certain conditions, it is equivalent to a solution provided by a decentralized model in which agents can decide for themselves.

Welfare analysis has become an important tool in applied modeling studies. It provides the opportunity for simulating social and economic driving forces of land-use change in a methodologically rigorous way. The combination of defining an ideal reference solution derived from welfare analysis and examining its sensitivity to specific myopic rules and behavioral assumptions seems to be a reasonable and policy-relevant approach to the comparative study of possible land-use and land-cover change trajectories.

Anthropogenic Driving Forces

A multitude of driving forces of land-cover change can be captured in the LUC analysis. Researchers have grouped the anthropogenic forces driving land-use and land-cover changes into several categories: population change, level of affluence, technological change, economic growth, political and economic structure, and attitudes and values (Stern *et al.*, 1992; Turner *et al.*, 1993).

A dominant driving force for land-use and land-cover change in most developing countries has been, and will continue to be, growth of consumer demand for agricultural and forestry products. Consumer demand is closely linked to population size and level of income.

Urbanization has been a global phenomenon in recent decades (e.g., Simpson, 1993). Rapidly growing numbers of urban consumers are increasingly determining the demand for food, fiber, fuel, and timber. A significant and growing fraction of production from agriculture and forestry is exchanged through domestic and international markets. Hence, in the future, the role of commercial production and markets will become increasingly more important than the role of rural subsistence producers. Consequently, opportunities for marketing, prices of commodities and production inputs (seed, fertilizer, etc.) will more and more influence the decisions of consumers and producers on land use and resource allocation.

In developed countries, where growth in population and per capita demand for food and wood products has leveled off, the dominant driving force of land-use change has often been the need to limit surplus production in agriculture (such as in the European Union) and privatization and economic restructuring (for example, in Eastern Europe and the former USSR).

Over the last decades, technological progress has been crucial to cope with increasing demand for land-based products. As late as the 19th century, almost all of the increases in world food production were achieved by bringing new land into production. By the end of 20th century, almost all of the necessary increases in world food production will have to come from higher yields. Technological progress in crop production has brought about intensification in both space and time. Higher yields per hectare of harvested area have resulted from improved seeds, increased application of fertilizers, better plant protection, and improved tools and mechanization. Cropping intensity has also increased, i.e., the average number of days per year that land is used for crop production has increased; this increase is due to irrigation and reduced fallow periods.

The main economic actors – producers and consumers – operate within the legal and institutional frameworks created by governments and international agencies. Subsidies and taxation create economic incentives and distortions that affect resource allocation and levels of use. Environmental standards for pollutants, as well as legal and economic instruments to achieve them, provide stimuli to technological innovation and to environmentally benign land use. Regulations can protect the environment by limiting polluting production activities and environmentally risky land uses.

The principal policy issues to be addressed by the LUC Project include the proper valuation of land resources, food security, sustainable agricultural development, and environmental protection. The vast region of Northern Eurasia is critical for analyzing both regional driving forces of global processes and regional implications of global processes when addressing these policy issues.

In Western Europe, the single most important driving force for future land-use changes is, and will continue to be, the Common Agricultural Policy (CAP) of the European Union. Policies within CAP are multifaceted, focusing on supply management, environmental integrity, rural incomes, and avoidance of agricultural trade conflicts.

In the former centrally planned economies of the USSR and Eastern Europe, the land-use situation is perhaps even more complex. A number of issues are under discussion: establishment of an efficient market system, privatization, modernization in agriculture and forestry, environmental problems such as contamination of soils, and the need for stability of political institutions.

In the past, Chinese agricultural production has been able to support a steadily growing population by stepwise increases in productivity and total output. The recent jump in production in the early 1980s was due to the 1979 rural reform. However, the impressive growth in output carried a heavy environmental price tag. Issues of land-resources analysis are focused on quality and amount of water supply, soil erosion, deforestation, air pollution, and increasing aridity. The problem now faced by Chinese policy makers is to identify environmentally compatible development paths for Chinese agriculture and, in more general terms, for managing land resources in China.

This brief discussion of driving forces shows that any sound effort to project future states of land use and land cover must capture the regional demographic and social trends, include the interplay between the supply of and the demand for major agricultural and forestry products, and address the influence of various policy measures on these interactions.[1]

Spatial Representation

A model for studying land-use and land-cover changes must be geographically explicit. The geographical representation should allow for sufficient differentiation of biophysical determinants of land productivity, and hence of land use, such as climatic conditions, soil characteristics, and land-form (i.e., physiography, relief intensity, slope, aspect). Representation of differences in social, economic, and political organizations is essential as well.

In our approach we subdivide the study region into compartments, or subregions. Compartments are defined to reflect structured entities, i.e., subsystems, of the broader region under consideration and their economic, as well as other, interactions.

Compartments are organized hierarchically, for example, by province, country, and group of countries with formal economic and political collaboration (e.g., the European Union). Since agents in the model are identified at the compartment level, technological, environmental, and financial constraints can be specified at various levels of aggregation within the hierarchy. These specifications allow the user to introduce elements that are specific to the region or subregion into the model. Decision-making can be represented at the appropriate administrative level. Local, national, and international markets can be simulated. Environmental constraints and mechanisms to enforce environmental agreements can be depicted at the relevant spatial and administrative levels. This structure allows for much flexibility in modeling driving forces operating on different spatial and organizational scales.

In practice, compartments will often be obtained by superimposing maps of different aspects of the land, such as administrative boundaries, social and economic organizations, climate zones, and landforms, and then drawing boundaries that best reflect the most important distinctions among these map layers. Geographical information systems (GISs) provide powerful assistance in storing and manipulating geo-referenced data. In the LUC Project, several geographic layers for the continental model are being assembled at a scale of 1:4 million. Climate, landform, soil, and vegetation maps form the backbone of the biophysical land characterization.

In the LUC model, compartments (i.e., their economic agents) interact through commodity trade and financial markets, and flows of mobile resources. They are affected by government policies, regulations, and other regional constraints. Compartments may interact through material transport and transboundary flows of pollutants. Human migrants generate demographic flows across compartment boundaries.

With respect to the interaction of different compartments, consideration must be given to an adequate representation of the physical flows of commodities in the LUC model system. Two aspects must be mentioned: transformation of commodities through processing when flowing from the production site (e.g., the farm) to the consumer; and transportation requirements to bridge distances when flowing to markets in different locations. For a tractable implementation, some simplifications must be adopted for both elements. A common method to reduce the complexity of a full trade matrix and to avoid possible indeterminacy of trade flows is to assume a trade pool into which all exports flow and from which all imports originate. This approach eliminates bilateral trade flows but retains information on transportation costs as well as constraints on routes to and from the pool. Transportation is thus interpreted as a means to homogenize commodities that were produced at different locations but have identical physical characteristics (Ginsburgh and Keyzer, forthcoming).

Temporal Aspects

A major task of the LUC Project is to study the sensitivity of land-use and land-cover change dynamics to various policies, behavioral assumptions, demographic and socioeconomic developments, and environmental conditions. Hence, dynamics is a critical issue in the modeling effort. The time span of the analysis covers the period from 1990 to 2050, which is subdivided into five-year intervals. Thus, the model is of discrete time with thirteen time steps, $t = 1,\ldots,13$. The initial step, $t = 1$, refers to year 1990 and the final step, $t = 13$, refers to the end of the model horizon, i.e., to the beginning of year 2050.

A discussion of the temporal aspects of modeling consumer and producer behavior in the LUC model requires to distinguish between model-endogenous and model-exogenous dynamics and to introduce intertemporal specifications of consumers' utility function and the producers' profit function. The objective is to describe how variables of interest change over time. Many factors may cause such changes. We group them into two sets: exogenous factors and endogenous factors.

Time-dependent exogenous factors include variables such as parameters that describe the shift in technology of production functions, changes in characteristics of agents, including changes in life-styles expressed through shifts in parameters and functional forms of the demand system, or changes in policy variables, such as trajectories of tax levels. Exogenous dynamic factors are easily implemented, by allowing for time-dependent functions in the model. Their introduction does not lead to any essential methodological complications and can be dealt with effectively by simple extensions of the static framework by means of recursive dynamic simulation. This involves computing a sequence of single-period equilibrium solutions for periods that are related through the updating of some parameters and exogenous variables.

Endogenous factors in the LUC model include components such as allocation decisions of consumers (for example, allocation of income to savings and consumption) and of producers (e.g., decisions on investment and resource use). A static model formulation is clearly insufficient when dynamics depend on endogenous factors.

Ideally, intertemporal welfare analysis should start from an infinite time horizon. Two conceptually different approaches exist to implement infinite-horizon models and to perform such an analysis:

- The first approach deals with a finite number of agents who live forever. For example, the initial population of a geographical unit and its descendants can be identified in this way. This kind of representation is called dynastic model. The basic mechanism to deal with intertemporal aspects of consumer decisions is to include so-called time-recursive consumer preferences. Each agent's (i.e., each dynasty's) well-being in period t is described as depending on current consumption as well as the well-being in the next period.
- The second approach considers an infinite number of generations; each generation lives at least two time periods, labeled young and old. Also, generations overlap – namely, the old agents of one generation live together with the young agents of the next generation. Such models are termed overlapping-generations models.

In the LUC Project, we start from the dynastic model specification. It is generally impossible to numerically solve a model with an infinite number of unknown variables or equations, as occur in infinite-horizon dynastic and overlapping-generations models. Infinite-horizon models and the solution techniques proposed also suffer from other theoretical and practical problems (see discussion in Gunning and Keyzer, 1995). Therefore, in the LUC Project we attempt to implement a finite-horizon approximation of the infinite problem.

Production Activities and Resource Dynamics

Modeling production activities relevant to land-use and land-cover change in a way that takes into account both environmental and socioeconomic conditions and changes is a challenging and ambitious task. The goal of the production component of the LUC model is to depict spatial and intertemporal allocation of land to various regional activities, such as crop agriculture, livestock grazing, forestry, energy production and mining, settlements and infrastructure, manufacturing, recreation, and nature reserves.

The production component includes processes of resource accumulation and degradation. The term *resource* is used in a general sense. Resources include human resources (with attributes such as population number, distribution, age structure, migration flows, fertility, and skill level), renewable and nonrenewable natural resources (including soils, minerals, water, and air), biological resources (such as biodiversity), and economic resources (capital stocks and machinery). Degradation encompasses physical degradation (such as soil erosion, degradation of soil structure, and changes in level of groundwater table) and chemical degradation (including loss of soil fertility, acidification, salinization, toxification of soils, and nitrification of groundwater).

A sequence of time periods is established in the model. Capital and environmental stocks in the current period serve as inputs in the production process. Net supplies of consumer goods and of stock levels at the beginning of the subsequent period are the results of production and investment activities. Hence, environmental resources enter as inputs into production and are, at the same time, affected by these production processes. Production activities are specified by quantity and quality of relevant resources. By explicitly dealing with resource accumulation, feedback mechanisms that act slowly on long time scales (such as soil erosion and aquifer depletion) can be represented.

To differentiate land resources with regard to land productivity according to physical properties, we define a number of *site classes* in terms of intrinsic land properties. Attributes that are considered include: temperature regime, moisture regime, landform and slope, soil type, phase, and texture, and land accessibility (approximated by infrastructure, population density, and other components).

To facilitate the creation of adequate site classes, the LUC Project is currently developing several continental-scale data bases in a GIS that includes climatic variables, vegetation, and land resources. Land characterization is described according to the specifications for global and national soils and terrain digital data bases (SOTER), which were recently developed (UNEP/ ISSS/ISRIC/FAO, 1995) and are gaining wide acceptance. In the SOTER approach, the main differentiating criteria for land characterization are physiography, terrain components, and soil components.

Land use is best described in a hierarchical way. At the highest level, we define trajectories of major land uses in each site class. Major land uses include natural/unused areas, protected areas, farmland, grassland, forests, residential areas, infrastructure, and mining areas. Within each major land-use class, several land-use types are considered, with well-defined purposes, operation sequences, and input/output relationships.

The two main processes of land-use and land-cover change – land conversion and land modification – are then described at different levels in this hierarchy. *Land conversion* is indicated by the reclassification of land from one land-use class to another. For example, areas in the natural/unused major land-use class could be placed in the agriculture class. *Land modification* occurs within major land-use classes and results from changing the allocation of land-use types; modifications could be due to changes in management practices or changes in the crop mix.

Risks and Uncertainty

Consumers, producers, and governments do not have access to all the information they need to maximize intertemporal utility and profit. They are faced with uncertainty about their external environment (prices, markets, weather) and about their own production set (productivity of workers, reliability of equipment). Insurance schemes, a common mechanism to cope with and to share risks, cannot be introduced for all possible uncertainties and risks involved. In practice, the objective is to combine economic schemes (like insurance policies), where they are feasible, with policies that are robust against possible surprises.

The land-use change study must deal with at least two different types of uncertainties. The first is objective uncertainty such as rainfall in a particular year. A model builder shares this type of uncertainty with the agents (such as farmers) in the real world. The second is uncertainty about the quantification and specification of relationships, such as the value of some technical parameters, or the political feasibility of implementing particular policies.

In the short term, the sustainable supporting capacity of a region, limited by prevailing conditions in bad years, depends on the region's ability to adapt to changing conditions, for example, through additional land-management measures, food storage, or finance of additional imports and infrastructure. In the extended long-term, strategic decisions are needed to keep pace with the changing needs in a region. In the LUC model, these aspects are taken care of by incorporating two types of mechanisms:

- Short-term adaptive (*ex post*) decisions such as use of irrigation water, level of fertilizer application, allocation of manual labor and machinery in a given situation, change of planting dates, and replanting of crops.
- Long-term strategic (*ex ante*) decisions such as investment in machinery, irrigation schemes, storage facilities, major land improvements, structure of livestock, and cropping patterns.

There is yet another issue of risk and uncertainty. Strategic (*ex ante*) decisions are defined as those that cannot be altered in response to an observed situation. Some strategic decisions, such as construction of a dam, use of nuclear energy, and deforestation of tropical rainforests, may involve irreversible transformations of the environment, or at least may be characterized as extremely costly in terms of options to reverse their impact. At the time when a decision must be taken, there is often considerable uncertainty about future costs and benefits associated with the irreversible decision.

Summary

The LUC Project is aimed at the analysis of spatial and intertemporal interactions among various socioeconomic and biophysical factors that drive land-use and land-cover change. Exact prediction of the outcomes of such complex systems over medium and long time horizons is impossible. Instead, we emphasize the need for comparative studies of the impacts from various demographic, economic, and political factors on the dynamics of land-use and land-cover change. Taking these studies into account, a model specification that explicitly introduces policies and decisions of economic agents becomes essential.

From an economic perspective, the interactions between climate, land resources, and vegetation are part of physical transformation processes of resource and capital stocks induced by human investments and disinvestments. An important aspect of economic analysis is that patterns and conditions of land-resources development and investment should be Pareto efficient, namely, that no one could be better off without someone else being worse off. In this analysis, equity considerations are obviously relevant as well. Otherwise, these investments may leave certain regions without sufficient resources or may deprive future generations.

The objective of the LUC Project is to describe socially desirable and economically efficient trajectories of investments and resource use. These trajectories represent a welfare optimum in which the levels of investments are determined and weights on the agents' utilities are set to satisfy budgetary (and other) constraints. Though such a solution may be regarded as unattainable, it can serve to distinguish real-world problems that are due to fundamental technical relations or to incompatible dynamics (for example, population growth) from those that are attributable to specific modes of social organization and institutional setting. While the former will persist in any projected trajectories of future development, the latter will only appear when one introduces imperfections in the decentralization of the welfare optimum.

To achieve the objectives outlined in this paper, the activities of the LUC Project in the continental-scale study are organized at three broad levels (*Figure 1*). The most general stratum is termed the *scenario framework*. Data collection and analysis at this level serve to embed the study region in the wider geographical global context and to develop trajectories of variables which are not dealt with in the LUC model but are important to consumers who derive income from non-land-based economic sectors (that is, other than agriculture and forestry) and to land managers who need information on policy formulation, technological development, and possible changes in the climate system.

The second stratum of the organization refers to the continental-scale study region. At this level, a geographic information system and data bases, the LUC-GIS, are being developed that will allow for various biophysical assessments of the dynamics of natural vegetation, land productivity, land degradation, and hydrology, and for the analysis of socio-demographic factors. These analyses are essential inputs to the data base and parameterization of the centerpiece of the LUC study, the LUC Core Model, which has been outlined in this paper.

Several case studies in representative ecological and socioeconomic settings are being undertaken in parallel to and in support of the development of the continental-scale LUC model. Local teams are implementing these case studies, which provide the opportunity for in-depth analysis of regionally specific land-use issues. A number of case study areas have been identified, and collaborating teams have already been established in China, Japan, and Russia.

Note

[1] There is a difference between projection and forecast. A forecast is a scenario whose outcome is considered most likely to occur. A projection is a quantitative assessment based on a number of assumptions, not necessarily the most probable ones, from the point of view of their combined occurrence.

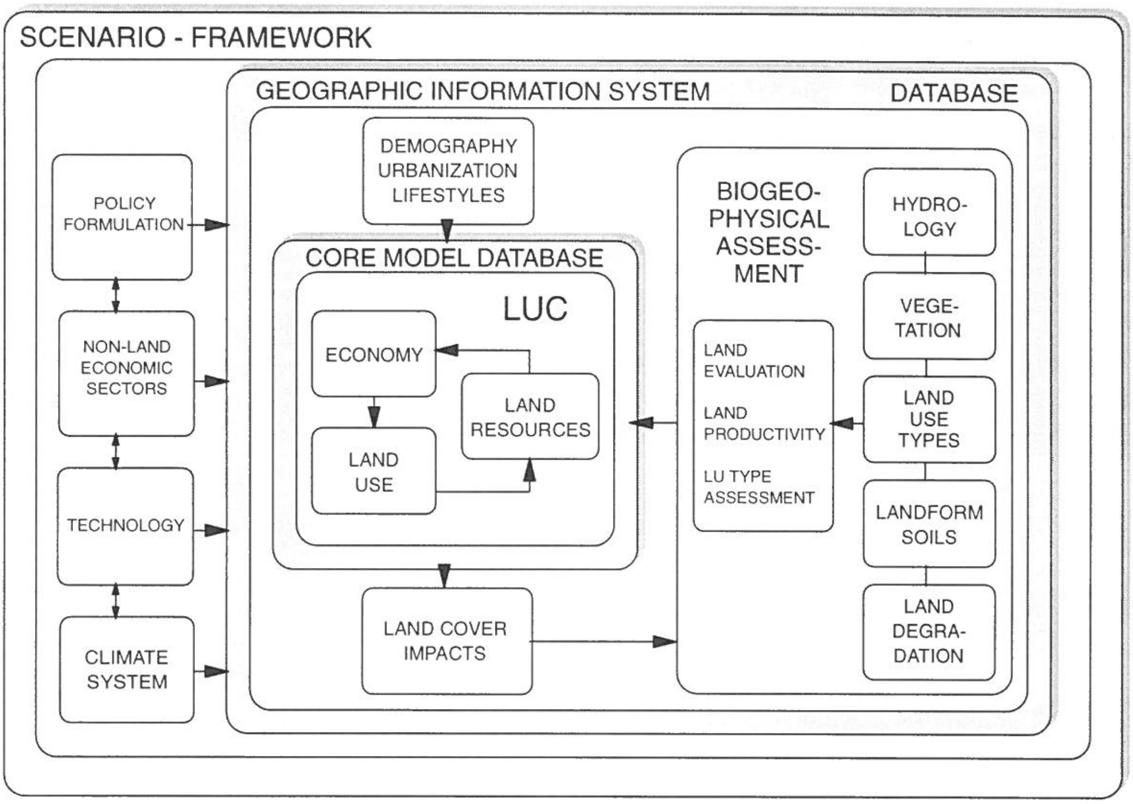

Figure 1: LUC modeling framework.

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An Asian Perspective of Energy and Environmental Development

Presented by

Markus Amann

Günther Fischer

Nebojša Nakićenović

An Asian Perspective of Energy and Environmental Development

Markus Amann, Günther Fischer, Nebojša Nakićenović

Asia currently has the world's fastest growth rates in economic activity. These growth rates are accompanied by a rapid increase in energy consumption. Simple extrapolations of current energy trends over the coming decades suggest a fourfold increase in Asian energy consumption within the next 50 years. This increase would make the region one of the world's largest emitters of carbon dioxide, an important greenhouse gas.

Are such scenarios realistic or would a wider scope of the analysis produce a more differentiated result? Could factors that are often ignored in conventional analyses become active constraints to the growth and thus modify future development? Integrated assessment offers a systematic approach to the study of a variety of different aspects in an interdisciplinary way.

IIASA's research aims at drawing together the experience and richness of disciplinary models developed within several research projects to discover new insights into the dynamics of global change. In an early exercise, the three energy models of IIASA's Environmentally Compatible Energy Strategies Project, the Regional Air Pollution Information and Simulation (RAINS) model developed by IIASA's Transboundary Air Pollution Project, and the Basic Linked System (BLS) of national agricultural models maintained by IIASA's Land-Use Project have been used to explore global and regional dynamics, constraints to and feedbacks for future development. This integrated assessment is also the core of a multiyear research effort between IIASA and CRIEPI in Japan.

The initial task of the exercise was the creation of a consistent linkage of the five models. Depending on their primary objectives, the models, which are well established in their fields, employ different time scales and spatial resolutions. Paths of interaction and feedback mechanisms between the models were defined, and data bases were harmonized to enable meaningful results.

This model system was subsequently used to explore the implications of coal-intensive energy systems in East Asia. The analysis shows that, in the absence of drastic abatement measures, a scenario with a high level of coal use would lead, within the next two decades, to excessive levels of acidic deposition and ambient SO_2 concentrations, levels twice as high as those in the currently worst affected areas of Central and Eastern Europe. This situation could threathen some of East Asia's most economically important agricultural ecosystems. In addition to significant local and regional environmental impacts, such a high growth, coal-intensive energy scenario would also produce extremely high emissions of CO_2. This would result in a statistical mean temperature increase of about 2.5°C. Without the regional cooling effect of sulfate aerosols induced by sulfur dioxide, the realized temperature increase would be even higher. Some effects of increased carbon dioxide concentrations might be beneficial and lead to increased agricultural production in Asia. Overall, however, a coal-intensive future would adversely affect the environment by generating climate change and increased acidification in Asia. Alternative energy strategies could yield reductions in both sulfur and carbon emissions. This will be the subject of further work at IIASA.

An Anticipatory Integrated Assessment of Regional Acidification: The RAINS-Asia Model

Presented by

Markus Amann
Project Leader, Transboundary Air Pollution

An Anticipatory Integrated Assessment of Regional Acidification: The RAINS-Asia Model

Markus Amann, Gregory R. Carmichael,[1] Wesley Foell,[2] Jean-Paul Hettelingh[3]

Introduction

Air pollution problems are becoming increasingly evident across large parts of Asia. Rainfall in some areas, including China, Japan, and Thailand, has been measured to be 10 times more acidic than unpolluted rain. Evidence of acidification damage to ecosystems, such as surface waters, soils, and economically important crops, is increasing. In addition, urban air quality in many areas of the region continues to deteriorate.

Current economic forecasts predict continued rapid economic growth in the region, which will bring with it increasing emissions of air pollutants, especially sulfur. The total primary energy demand in Asia currently doubles every 12 years (as compared with a world average of every 28 years). Coal is expected to continue to be the dominant energy source, with coal demand projected to increase by 6.5% per year; this rate outpaces regional economic growth. If current trends in economic development and energy use in Asia continue, emissions of sulfur dioxide, one of the key components in acid rain, will more than triple within the next 30 years. Many ecosystems will be unable to absorb these increased levels of pollution without harmful effects, thus creating the danger of irreversible environmental damage in many areas.

In view of the potential environmental consequences of projected growth in Asian energy consumption, emissions, and air pollution, the World Bank, together with the Asian Development Bank, funded a project to develop and implement an integrated assessment model of the acid deposition phenomenon in Asia. The Regional Air Pollution INformation and Simulation model for Asia (RAINS-Asia) is a software tool to help decision makers assess and project future trends in emissions, transport, and deposition of air pollutants and their potential environmental effects.

The RAINS-Asia Model

To create a practical tool for scenario analysis, the model defines simplified relationships between input data (e.g., economic development for the energy module, annual emissions of the atmospheric module, and deposition for the effects module) and the output variables (annual emissions of the energy module, deposition of the atmospheric module, and potential ecosystem damage of the effects module).

[1] University of Iowa, Iowa City, IA, USA.
[2] Resource Management Associates, WI, USA.
[3] National Institute of Public Health and Environment, Bilthoven, Netherlands.

The model uses these relationships to develop an overall assessment framework, allowing the comparative analysis of alternative energy and emission reduction strategies. The RAINS-Asia model consists of various modules; each module addresses a different part of the air pollution/acidification process:

- The Regional Energy Scenario Generator (RESGEN) module estimates energy consumption patterns based on socioeconomic and technological assumptions.
- The Energy and Emissions (ENEM) module uses these energy scenarios to calculate sulfur emissions and the costs of selected control strategies.
- The Deposition and Critical Loads (DEP) module consists of two submodules. The ATMOS atmospheric transport and deposition submodule calculates the levels and patterns of sulfur deposition resulting from a given emission scenario. The IMPACT submodule calculates ecosystem critical loads and their environmental effects, based on sulfur deposition patterns.

The regional energy scenario generator (RESGEN) module

The RESGEN module estimates present and future energy supply and consumption levels based on a variety of socioeconomic and technological assumptions. Given a set of specifications concerning current and future conditions (using either the extensive socioeconomic and energy demand and supply data bases in the model or user-specified alternative assumptions), the model calculates energy scenarios for the period 1990 to 2020. These energy scenarios can then be used as input to the RAINS model to calculate sulfur dioxide emissions, deposition, and environmental effects.

The RESGEN module is structured to provide answers to different types of policy-relevant questions, including:

- What are the effects of changes in population and economic growth on future energy demand?
- How do economic and development policies for various sectors affect energy production and consumption patterns?

Using RESGEN a user can select, review, and modify key parameters at the regional level, including:

- **Socio-economic data** – Rates of population growth and GDP growth are divided into industrial, agricultural, and commercial/other components.
- **Growth rates of energy demand among six end-use sectors** – This parameter considers energy demand from industry, transportation, residences, commerce, agriculture, and other uses. Energy supply and transformation systems are subdivided into electricity generation, oil refining, and other industrial operations.
- **Energy intensity** – This parameter measures energy demand per unit of economic activity for each of the six end-use sectors.
- **Fuel types used** – Since SO_2 emissions are highly dependent on the type and characteristics of the fuel(s) used, the model considers 17 different fuel types, including various qualities of coal, other solid fuels, fuel oil, natural gas, renewable sources, hydropower, and nuclear.
- **Fuel characteristics** – This parameter considers the sulfur content of various fuels.

For RAINS-Asia, a network of Asian energy research institutions was established to collaborate in developing regional data bases and energy scenarios. The Asian Institute of Technology (AIT) in Bangkok was designated as the coordinating center for the network and was responsible for collecting the necessary data at the national and regional levels and for establishing long-term ties to key institutions and potential model users.

To measure the effects of various energy policies and control strategies, two energy demand scenarios have been developed to describe possible future energy pathways for the Asian region: the *base case pathway* and the *efficiency pathway*. The base case scenario relies on official energy projections from individual countries whenever available. Business-as-usual policies were assumed in areas for which future economic or energy data are incomplete or unavailable, and are based on historical or expected trends.

The energy-emissions-cost (ENEM) module

The Energy and Emissions (ENEM) module of the RAINS-Asia model uses the information on energy demand, types of fuels used, and location of major emission sources developed by the RESGEN module. From this information it estimates the resulting amounts and patterns of SO_2 emissions and the costs of various control options.

The ENEM module contains energy and emissions data bases (developed primarily from in-country data sources), covering 94 regions in 23 countries, including 355 individual large point sources (such as large power plants or industrial sites). It allows users to choose future energy scenarios, calculate the resulting emissions levels, and answer various policy-related questions such as:

- What will future levels of sulfur emissions be for a given economic/energy scenario?
- What control strategies are available to reduce sulfur emissions, and what are the estimated costs to implement these controls?
- What effects do changes in energy efficiencies have on resulting sulfur emissions?
- What environmental improvements would result from the relocation of a large emission source from a sensitive ecological area to a less sensitive region?

While the necessary data were available for some countries from previously published studies, for many countries this information had to be developed from secondary sources. Data were compiled on energy use by fuel type and geographic region, the size and location of large point sources, and fuel characteristics (sulfur content, emission factors, etc.) for various fuels. The model includes emissions data developed specifically for this project from 17 countries, and previously published emissions estimates for 6 other countries. The network of energy research institutions played an instrumental role in gathering these data.

The ENEM module also performs cost calculations for implementing the emission reduction strategies selected. The model calculates total life-cycle costs, including investment-related start-up costs (such as installation, construction, and working capital), fixed operating costs (such as maintenance, taxes, and overhead), and variable operating and maintenance costs (such as additional labor and waste disposal). The parameters used in the calculations are determined to be either common or country-specific. Common parameters, which apply to a specific technology, include installation lifetime, sulfur removal efficiency, and energy and material requirements. Country-specific parameters include such items as interest rates, average plant capacity utilization, boiler/furnace size, and energy and material prices.

The module also produces national cost curves that rank the available abatement measures by their overall cost-effectiveness. Since factors such as energy-use patterns and technological infrastructure differ greatly between countries in the region, there are large differences in these national cost curves.

The atmospheric transport (ATMOS) module

The ATMOS submodule is a long-range transport and deposition model of sulfur in Asia. The submodule calculates sulfur dioxide and sulfate concentrations and wet and dry deposition which result from various energy/emissions scenarios generated by the RESGEN and ENEM modules. ATMOS incorporates an atmospheric source/receptor relationship, calculating sulfur transport and deposition, across all of Asia on a 1°-by-1° grid. The model can be run for an entire year for each source identified, calculating the total annual deposition attributable to that source. Similarly, when run for all sources and areas, the model calculates the total annual deposition over the entire model region. Thus, ATMOS can be used to answer questions such as:

- How do changes in energy consumption and emissions from a specific area, or a single large point source, affect levels of acid deposition in other areas?
- What sources or areas contribute to sulfur deposition in a given region?

An ATMOS focal center was established at the Center for Atmospheric Sciences, Indian Institute of Technology (IIT) in Delhi. This focal center serves as the hub of communication and activities related to the development and use of the ATMOS model.

The ATMOS submodule uses input data on emission rates and levels and source locations (from ENEM) as well as meteorological data (including wind direction and speed, temperature, and precipitation rates) from international organizations or national sources where available. Data on emissions supplied by the ENEM module contain both anthropogenic and natural sources, including large point sources, area emissions (subdivided into industrial, domestic, and transportation categories), shipping activities (including regional shipping lanes and harbor activities), and active volcanoes.

The model uses meteorological data of the US National Oceanic and Atmospheric Administration from approximately 200 stations in the region and precipitation data from the National Center for Atmospheric Research, as well as data compiled at monitoring sites in the region. The model provides annual average (wet + dry) sulfur deposition values and monthly average SO_2 concentration values for each 1°-by-1° grid cell. Concentration and deposition values are calculated separately for large point sources and area sources. For dispersed area sources, the results are aggregated, showing each region's contribution to deposition in a particular grid cell. Emissions from each large point source are calculated individually, providing the contribution of each source to each grid cell. This component allows the model user to assess the spread of pollution from an individual source or region and to identify emission sources that contribute to sulfur deposition at a particular site.

Since most existing SO_2-monitoring stations in the region are in urban areas, it was necessary to gather more base-level data for further model evaluation. A notable result from phase I of this project has been the initiation of a network of inexpensive sulfur dioxide air samplers at 43 sites in 11 countries to obtain more broad-based monitoring data for the model.

The ecological impacts (IMPACTS) submodule

The IMPACT submodule assesses the sensitivity of various ecosystems (their *critical load*) to acidic deposition, and compares this information to the deposition data generated by the ATMOS submodule. This process identifies the most ecologically sensitive areas that are at greatest risk of damage from present or projected levels of sulfur deposition.

A critical load of an ecosystem is essentially the *no-effect* level for a pollutant, that is, the level of a substance (acid deposition, as an example) which does not cause long-term damage to an ecosystem. Areas which have a limited natural capacity to absorb or neutralize acid rain have a low critical load. Ecosystems which are better equipped to buffer acidity (through different soil chemistry, biological tolerances, or other factors) have a correspondingly higher critical load. Assessing the natural capacity of ecosystems to withstand current and projected levels of pollution is a method of measuring ecosystem health, and can serve as a way to assess the environmental benefits of emissions reductions.

By estimating critical loads for various regions and ecosystems, and comparing these natural sensitivities to deposition levels, the IMPACT submodule allows users to assess the environmental effects of different energy and emissions scenarios, answering questions such as:

- Which regions and ecosystems are most sensitive to acid deposition?
- What is the geographic scope and extent of ecosystem damage that result from a particular energy scenario?
- What environmental benefits would be realized if a particular emission control strategy were implemented?

The coordination center for the IMPACT submodule was established at the Research Center for Eco-Environmental Sciences in Beijing. The center serves as a focal point for the collection of national input data; investigators at the center work together with a network of environmental researchers from several Asian nations and Western collaborating institutions. A geographic information system (GIS) and critical loads models were installed at the center, and training was provided through periodic exchanges of personnel.

Critical loads have been computed and mapped in Southeast Asia, comprising China, Korea, Japan, the Philippines, Indochina, Indonesia, and the Indian subcontinent. The methodology used the steady-state mass balance (SSMB) approach adapted to Asian characteristics. In Asia critical loads have been computed for 31 different types of vegetation. The computation of critical loads is based on plant response criteria and soil stability criteria for each vegetation type, including both natural and managed ecosystems. A critical molar ratio of the concentrations of base cations to aluminum in soil solution (BC/Al) for each plant species is used as an indicator of plant response. Using these critical BC/Al ratios in the SSMB method it is possible to compute maximum allowable acidifying deposition, i.e., the critical load. Critical values for BC/Al as thresholds for root growth reduction have been established for many plant species. The soil stability criterion is also introduced to avoid acid deposition leading to aluminum leaching in excess of aluminum produced by weathering and other processes, e.g., in high precipitation areas. Critical loads for each ecosystem are computed by taking the minimum of either the plant-response-based result or the soil-stability-based computation of critical loads. Other data, i.e., climate, soil, geology, and vegetation data, and their geographical distribution, required to compute and map critical loads have been derived from a variety of sources.

The steady-state mass balance approach was applied in Asia in conjunction with the semi-quantitative method of relative sensitivity in order to compare the areas with stock at risk. The uncertainty of the critical load estimates is largely due to the uncertainties of base cation weathering and base cation deposition estimates, which require further verification.

Several simplifying factors have been incorporated into the present version of the IMPACT submodule. Only the indirect environmental effects of sulfur deposition (i.e., acidification) have been considered in this approach; direct effects, such as damage to vegetation from elevated SO_2 air concentrations, have not yet been considered in the model. As with all other parts of the RAINS-Asia model, the IMPACT submodule looks only at the role of sulfur in acidification. Nitrogen also plays an important role in the acidification process; however, during the first phase of the project, emphasis has been on the effects of large-scale SO_2 emissions and deposition.

Model integration and implementation

The region covered by the model ranges from 10° south latitude to 55° north latitude and from 60° east longitude to 150° east longitude, comprising the countries of East, South, and Southeast Asia. The model uses 1990 data as the base year, and calculates future energy, emission, and environmental parameters through the year 2020, at 10-year intervals.

While the model's geographic scope is broad, it is also detailed, distinguishing a total of 94 regions in 23 countries. Twenty-two of these regions are major metropolitan areas; international sea lanes constitute one region. The model's data bases also include detailed information on 6 end-use energy consumption sectors, 17 fuel types, 355 large point sources of SO_2 emissions, 9 soil types, and 31 ecosystem types, including 15 types of vegetation.

The model runs on standard IBM-compatible computers and is user-friendly. Each module is set up to guide users through the sequence of steps necessary for creating and evaluating emission control plans.

Initial Model Results

A number of preliminary analyses have been carried out using the RAINS-Asia model. The model provides the first comprehensive, integrated analysis of the environmental consequences of continued uncontrolled growth of energy consumption and sulfur emissions in the region. In addition, various control strategies to limit sulfur emission levels can be investigated, and the resulting pollution levels and environmental effects explored.

An extrapolation of current trends to the year 2020

The first step in using RAINS as a tool for integrated assessment is the development of projections of future energy use in the region through the RESGEN module. The *base case* energy pathway assumes that countries in the region continue present energy policies, without any strong efforts to implement energy efficiency measures or to substitute current fuels for lower-polluting fuels. Official energy demand forecasts from individual countries were incorporated into this scenario wherever available. The projections resulting from this base case show that energy demand will more than triple from 1990 to 2020, with coal and oil remaining the principal fuels.

Using base case projections of total energy consumption, a similar disturbing picture emerges for sulfur emissions resulting from a policy of rapidly increasing energy usage over the next 30 years. Because of the high rate of economic growth forecasted for the region, and the concomitant increase in pollution levels, the lack of further action to control sulfur emissions would cause emissions to more than triple, from 33.6 million tonnes in 1990 to over 110 million tonnes by 2020, an increase of 230%. The combustion of coal for energy production and industrial uses generates approximately 75% of the sulfur dioxide emitted. The most rapid growth rate is seen in the power plant sector, due to the increased use of coal to generate electricity.

The expected rate of increase in SO_2 emissions over the next 30 years varies markedly from country to country. Emissions in many countries (e.g., Pakistan, the Philippines, Singapore, Vietnam) are poised to grow to five to ten times their current levels, while emissions in more industrialized countries (e.g., Japan) would increase at a slower, but still noticeable, rate.

The huge increases in energy consumption and SO_2 emissions envisioned under the reference scenario will bring about similar increases in sulfur deposition. *Figure 1* shows the result of ATMOS calculations of sulfur deposition patterns under the reference scenario in 2020. Large parts of eastern China and most of India would receive between two and five grams of sulfur per square meter per year. Many industrialized areas of Thailand, the Philippines, Indonesia, and Malaysia would experience sulfur deposition levels of five to ten grams per square meter per year, while local *hot spots* in some industrialized areas of China would receive about 18 grams of sulfur every year. (In comparison, the maximum levels reached in the most heavily polluted parts of Central and Eastern Europe are approximately 15 grams per year.)

As expected, the enormous growth in emissions and deposition under the reference scenario would lead to significantly high levels of ecosystem damage. *Figure 2* presents excess sulfur

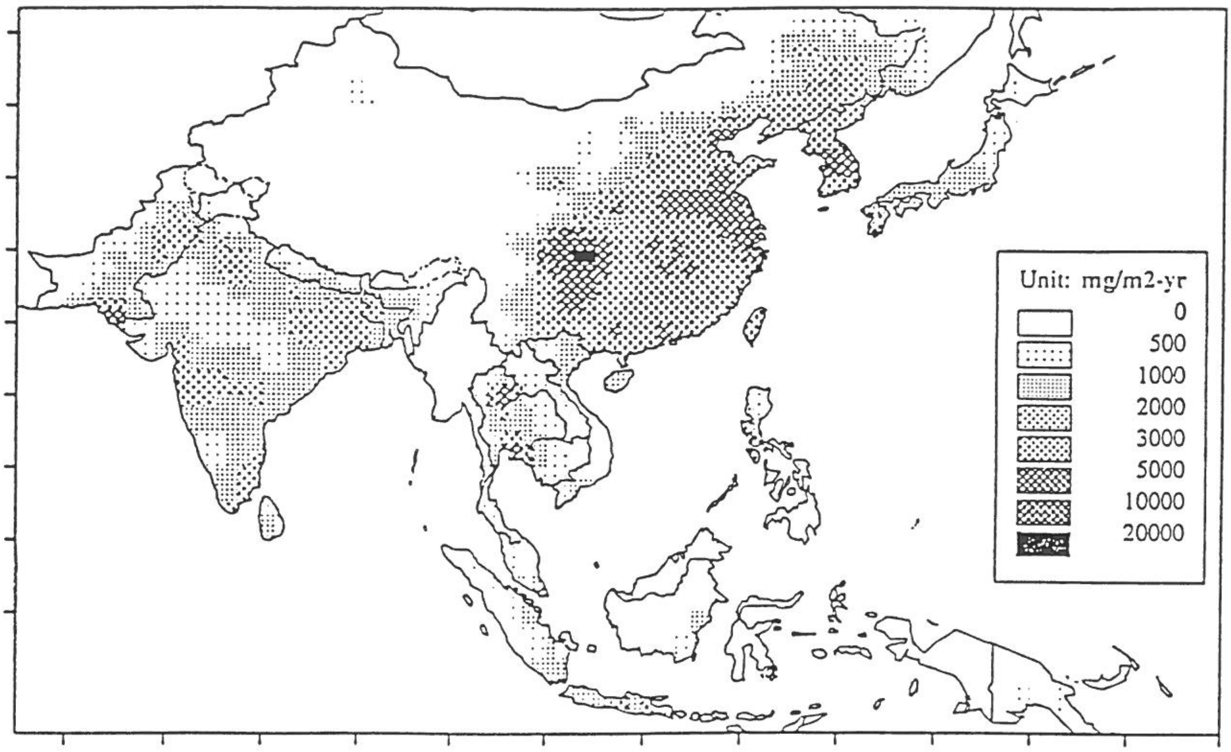

Figure 1: Sulfur deposition in 2020 under the reference scenario. Source: Carmichael and Arndt, 1995.

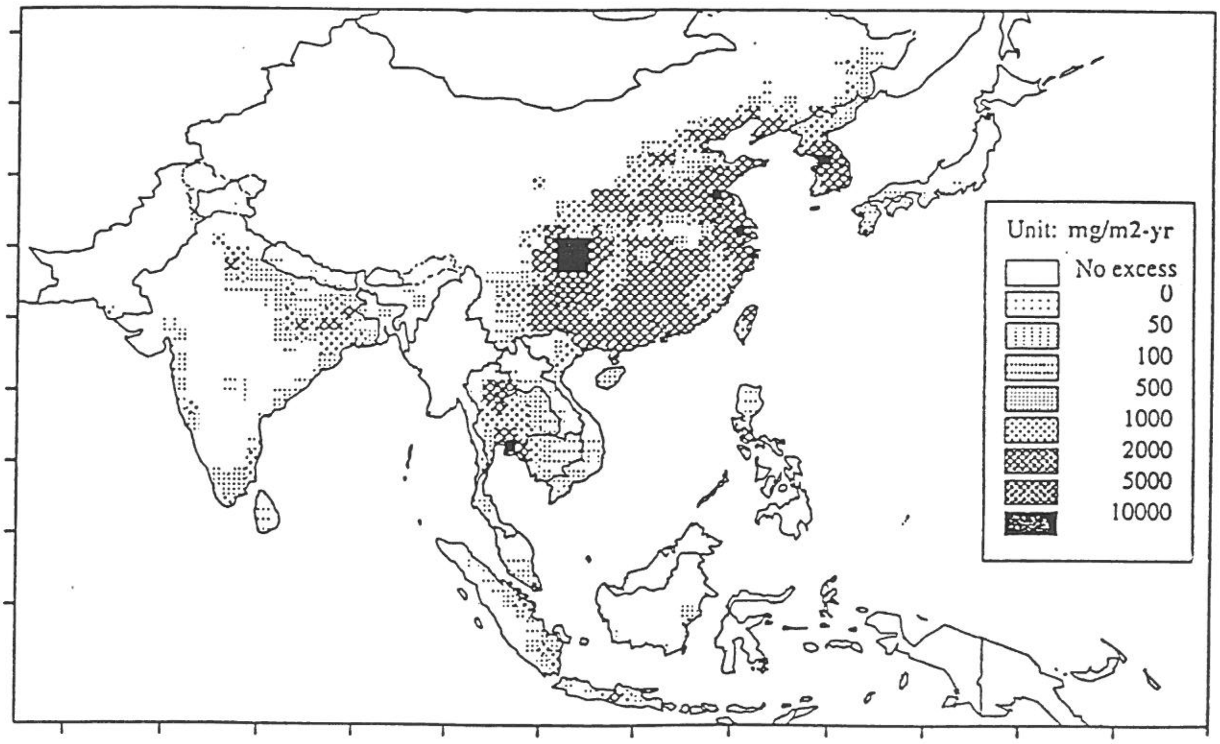

Figure 2: Excess sulfur deposition above critical loads in 2020 under the reference scenario.

deposition (that is, deposition which exceeds the critical load) in the year 2020. The map shows that large portions of northern and eastern India, southern and eastern China, parts of northern and central Thailand, and much of the Korean peninsula will experience sulfur deposition levels that exceed the ecosystem critical load in those areas. Other regions such as Pakistan, western and central India, western China, Myanmar, and parts of Indonesia would receive little or no excess sulfur deposition.

Due to the wide variety of ecosystem types and climates in Asia, the complexities of the biogeochemical processes involved in the acidification process, and the lack of local monitoring data, it is not currently possible to precisely quantify the environmental damage resulting from excess sulfur deposition depicted in these scenarios. The fact that some areas could receive 10 times (or even more) more sulfur than their ecosystems can tolerate, however, indicates the potential for widespread ecosystem injury. The IMPACT module can also investigate effects on individual types of ecosystems, such as agriculture, generally, or rice paddies, in particular. Similar results, showing excesses of up to 15 grams of sulfur per square meter per year under the reference scenario, have been calculated for rice paddies.

High levels of SO_2 concentrations are also predicted under the *no-control* policies assumed in the reference scenario. The grid-based model calculations show large areas, particularly in China and India, near or exceeding World Health Organization guidelines for ambient air quality. Urban air quality monitoring data tend to indicate that SO_2 levels in cities are considerably higher than the grid-average values calculated by the model. Additional investigation of urban air quality issues is expected to be a key part of the further development of the model.

Emission control scenarios

A major objective of the RAINS-Asia model is the assessment of costs and benefits of alternative strategies to reduce emissions. A number of emission control scenarios have been explored.

In contrast to the base case scenario, which assumes that no new measures are taken to control emissions, the *best available technology* (BAT) strategy investigates the results of implementing state-of-the-art pollution control technologies in many sectors. In this scenario, wet flue-gas desulfurization technology would be installed at all current and planned large point sources that burn coal or oil. Low-sulfur fuels (coal and oil) are assumed to be used in the residential/commercial and transportation sectors.

Through the widespread introduction of advanced control technologies to many sources, the RAINS-Asia model shows that drastic reductions in sulfur dioxide emissions can be achieved. Under this approach, SO_2 emissions would be cut by more than half in 30 years, from a 1990 level of 33.6 million tonnes to 16.3 million tonnes by 2020. The impact on deposition levels and critical loads excesses, is also remarkable. Nearly all areas will reach sustainable levels of sulfur deposition, i.e., levels that avoid ecosystem damage. Some remaining problem areas would still exist, however, including those near the border between Hunan and Jiangxi provinces in China, an active industrial area with very sensitive ecosystems.

Just as striking as the environmental improvements are the costs associated with the extensive implementation of stringent control methods. It is estimated that in the year 2020 costs to carry out BAT efforts across Asia would approach US$90 billion per year, or about 0.6% of the region's gross domestic product. Each country's financial burden would depend on its level of economic development and reliance on heavily polluting fossil fuels, which ranges from 0.05% of GDP Myanmar and 0.06% in Japan to 1.7% in China.

Because the BAT approach would impose significant financial burdens on many developing countries in the region, other scenarios were developed to try to identify more cost-effective measures to reduce sulfur emissions. With the objective to protect sensitive ecosystems, it is possible to rank a variety of control techniques by their cost-effectiveness (i.e., how much sulfur is reduced for a certain

Table 1: Comparison of emission and control costs of the base case energy pathway with the energy efficiency pathway, for three different scenarios.

Energy pathway	Emission control scenario No further control	Advanced control technology	Best available technology
Emissions in million tonnes of SO_2:			
Base case	110.5	50.4	16.3
Efficiency	80.1	39.1	12.4
Costs in billion US dollars per year			
Base case	3.9	38.8	90.4
Efficiency	2.0	25.5	65.6

Source: Amann and Cofala, 1995.

amount of money) and to implement only those required to achieve critical loads. The *advanced emission control technology* (ACT) scenario is one possible option; it selects those control methods which reduce sulfur emissions at the lowest cost.

Using this approach reduces the costs involved in emissions control, but it also achieves less than the BAT approach. In fact, SO_2 emissions would increase to over 50 million tonnes by 2020, a 50% increase from 1990 levels. This increase, however, is still less than half of the future emissions level of 110 million tonnes calculated under the no-control reference scenario.

The ACT scenario entails considerably lower costs than the BAT approach. The estimated total cost is US$39 billion per year, as compared with the BAT's US$90 billion figure. National costs again vary from country to country, although they are uniformly lower than those under the BAT scenario. The pan-Asian costs to implement this scenario would drop to 0.25% of GDP, a figure roughly equivalent to that established in the recent European agreement to reduce sulfur emissions (0.21% GDP).

Further improvements of cost-effectiveness can be achieved by focusing emission control measures on ecologically sensitive zones. The RAINS-Asia model, with its data base of 355 individual large point sources, provides a tool for designing such strategies.

Also energy efficiency measures are important cost-effective options for reducing emissions in many cases. As these structural improvements in the energy system lead to reduced fuel consumption, and thus reduced SO_2 emissions, the resulting SO_2 control costs are lower than the comparable strategies which are based on base case energy projections. *Table 1* compares emission levels and control costs of three scenarios for both energy pathways. Such measures often produce other secondary positive effects, in addition to reducing SO_2 emissions, such as lower CO_2 emissions, the replacement of inefficient capital stock, and a reduction in overall energy demand that in turn can improve trade balances.

Conclusions

The RAINS-Asia model is now available as a tool for analyzing cost-effective strategies to control sulfur emissions in Asia. Preliminary model calculations demonstrate that a continuation of the business-as-usual approach to energy development in the Asian region, given the large increases in energy consumption planned over the next 30 years, will lead to unparalleled levels of sulfur pollution.

Model calculations of possible future scenarios of energy use and sulfur pollution in Asia also show that steps can be taken to avoid the most drastic consequences resulting from continued uncontrolled energy and emissions growth. Although the costs are substantial, the model can help realize maximum benefits from measures taken.

The RAINS model provides an opportunity for assessing regional environmental impacts, and associated costs, of various national and regional energy development strategies. A key prerequisite for further refinement of the model is feedback from the model's end users (scientists, researchers, and policy makers in the regions) who have thoroughly tested the model's assumptions and input data, and have analyzed, disseminated, and implemented the model findings.

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