THE IIASA SET OF ENERGY MODELS: ITS DESIGN AND APPLICATION

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PREFACE

In November 1976, Academician Michail Styrikovich of the Academy of Sciences of the USSR urged me to make the Energy Systems Program studies more comprehensive by building a set of computer models to deal with the many interrelated issues of the prospects for energy, and to apply these models to each of several regions of the world. With this impetus, we began to design a set of models for our use – adapting existing models where possible, building new ones where necessary. Many people have contributed vitally to this task, beginning – even before Academician Styrikovich's request – with Alan Manne's and my dynamic linear programming energy supply and conversion model.

During the course of designing and building the models, cooperation with Dr. Kenneth Hoffman, then Head of the National Center for the Analysis of Energy Systems at Brookhaven National Laboratory in the USA, and with Professor Alexej Makarov and others at the Siberian Power Institute (SPI) of the Siberian Branch of the Academy of Sciences of the USSR helped greatly. It is no coincidence that the set of energy models of the International Institute for Applied Systems Analysis (IIASA) bears a strong resemblance to a set of models at SPI. The methodology and the analytical approach described in this report is the core of our work for the United Nations Environment Programme (UNEP), under the project "Comparison of Energy Options, a Methodological Study," which was sponsored jointly by UNEP and IIASA.

This report presents the status and operation of and plans for the IIASA energy models as of the end of 1979. Its author, the Assistant Leader of the Energy Systems Program, for the past two years coordinated and led the modeling team in their analysis of global energy scenarios. This paper is an up-to-date statement of the conception, design, and implementation of the main analytic tool of the Energy Systems Program. It is an important documentary backup to the overall results presented in the final report of the Energy Systems Program Group, *Energy in a Finite World, A Global Systems Analysis*.

Wolf Häfele
Deputy Director
Program Leader
Energy Systems Program

SUMMARY

A set of models for evaluating alternative energy scenarios has been developed and applied at the International Institute for Applied Systems Analysis (IIASA). The model set, long in development and following the initiative and guidance of Professor Wolf Häfele, includes several models: an accounting framework type energy demand model, a dynamic linear programming energy supply and conversion system model, an input–output model for calculating the impacts of alternative energy scenarios, a macroeconomic model, and an oil trade gaming model. The models have been designed into an integrated set for long-term, global analyses.

The models together are a set that makes use of a highly iterative process for energy scenario projections and analyses. Each model is quite simple and straightforward in structure; a great deal of human involvement is necessary in applying the set.

A first application of the models to study two alternative energy scenarios for 50 years has been completed. Some samples of the results reveal the wealth of information common to many modeling techniques.

Several of the models are documented so that details of equations, assumptions, and data can be observed.

CONTENTS

INTRODUCTION: ABOUT IIASA's ENERGY SYSTEMS PROGRAM

Energy modeling at the International Institute for Applied Systems Analysis (IIASA) is part of the Energy Systems Program, a research program which focuses its attention on the energy *transition* – the slow, but profound shift from the present energy system to a future sustainable one. The Program's primary considerations are long-term ones, spanning a horizon of 15 to 50 years from now. Within this period, the Program's findings indicate that many characteristics of the coming energy transition will be seen and felt.

To be sure, long-term considerations rarely find place in the thinking and planning of those who must make policy and investment decisions today. Yet, as energy systems become increasingly interdependent and increasingly widespread, the resulting inherent inertia or "braking distance" necessitates a long-term view, lest governments, businesses, and investors arrive at the crux of the energy transition having done too little too late. The big decisions in a shrinking world have big and long-lasting implications. Long-term views *are* in order; IIASA's energy study was conceived with this in mind.*

The study's considerations are also necessarily global ones; the present and future large-scale supply and use of energy mandates a degree of global interdependence that is unprecedented.

The IIASA Energy Systems Program concentrates on physical, engineering, and (some) economic aspects of the energy transition. Long-term energy options are, after all, ultimately based on technical realities. The Program explicitly does not take into account institutional, political, and most social

*The conception and guidance of IIASA's Energy Systems Program has been, since its inception, the work of Professor Wolf Häfele, the Program Leader. He has also guided the development of the model set described in this report.

aspects of the general energy question, although it is designed to provide a frame within which to deal with these issues.

The study makes use of scenario writing as a principal tool to investigate energy futures. These scenarios are not predictions, as the future is unpredictable; however, conducting studies such as these is necessary for responsibly dealing today with implications for tomorrow.

A number of initial views and assumptions about the energy problem helped to shape and design the approach used.

- Energy systems today are based on cheap oil and gas supplies; the world's expectations of such fuels and producers' ability or willingness to produce such amounts are very likely to come into conflict very soon. (This observation is made as a central conclusion in a number of recent reports, notably WAES 1977.)
- As a result, there will almost certainly be continued increases in world energy prices; this new environment contrasts with the past of constant and, in many cases, falling real energy prices.
- Scientific and technological development will contribute to a new capital intensiveness in energy systems that could have large feedback effects on economies. Whether energy systems are large and centralized or small and dispersed, the world will almost certainly have to face large energy investments in the near and long-term future.
- Developing countries and regions will have legitimate and growing needs for an array of energy and power supplies at affordable costs. Rising prices and increasing capital intensiveness could most adversely impact developing regions.
- Care for the environment is a critical, relatively new, and growing factor and will continue to participate directly in future global decisions in the energy arena.

The Energy Systems Program, which completed its first major phase at the end of 1978, has many tasks. It assesses energy systems in terms of resources and demands and it identifies the features of three major long-range energy options, namely, nuclear by breeding, large-scale solar power, and coal. The Energy Systems Program further considers constraints on future energy strategies such as man's possible impact on the climate by waste heat and/or CO_2 release, the perception of risks by societies, and time delays in energy systems development. All this is done with a view to the conception of energy strategies for the transition to future sustainable systems. The IIASA energy modeling effort described in this paper is an attempt to quantify the findings and results of these Energy Systems Program research tasks.

The modeling is, in a very real sense, the *synthesis* of the several tasks within the Energy Systems Program. The intent is to bring the several elements together in order to identify overall energy strategies for the long term and to evaluate the possibilities for integrating such strategies into the economy, the environment, and the society. The complexity of the energy transition demands careful analysis of all of the interrelationships. Such analysis, while not achievable only with computer models, could be seen as the central purpose and strength of energy modeling.

In its Energy Systems Program and as a part of the modeling effort, IIASA has established many links to both its National Member Organizations and various international institutions. An important contract with the United Nations Environment Programme (UNEP) in Nairobi called for developing a methodology for comparing energy options. That work (now complete) has been an integral part of our studies. Also, similarities in approach have been found with the set of models developed at the Siberian Power Institute of the Siberian Branch of the Academy of Sciences of the USSR, and continuous and active interaction with that group has greatly aided our program. [This cooperation is summarized in Häfele and Makarov (1977).]

A final introductory remark is relevant here. While the IIASA energy modeling effort is, to some extent at least, global in nature, it is not parallel to the wide-ranging global modeling of Meadows and Meadows (1972) and Mesarovic and Pestel (1974). Instead, the modeling work reported here clearly focuses on the medium- and long-term aspects of the *energy* problem; other domains are taken into account as necessary.

In this report, the purposes and goals of the energy modeling activity at IIASA are considered. Then, after touching upon some methodological issues, a profile of the activity is drawn: the general conception of the scheme and an overview of its design, structure, and scope. Finally, some selected illustrative results are given. The Appendixes contain short descriptions of each of the models in the set, and references of reports that give more complete documentation for the models are listed after the Appendixes.

This report is neither a summary of IIASA energy research nor a comprehensive recitation of results. It is simply a description of one piece of the overall effort: the integrated set of models.

PURPOSE AND GOALS OF ENERGY MODELING

Given a subject as complex, confused, and polarized as is current thinking about the world's future energy prospects, one might well ask why computer models should be thought to offer much help. It is a fair question, especially in light of recent escalations in such modeling efforts by many groups, with as yet nonobvious (or at least nonimplemented) benefits. Perhaps clarifying the general purposes of computer modeling will help place the possibilities of the machine in an appropriate context and thereby aid in identifying the real utility and benefits of such models.

Computer modeling has one central and specific purpose: to aid in understanding the complex interrelationships within systems – economic, technical, social, or in this case, energy systems. There are many interrelationships to be studied: technologies and capital, energy needs and economic activities (so-called energy-GDP ratio), energy supply and emissions and other environmental effects, energy conservation and energy supply, interfuel substitutions and structural economic changes. A fuller understanding of these and other fundamental interrelationships is a great strength of modeling analysis. Revealing structure and interrelationships is a much more appropriate, and feasible, role for models than the too often chosen objective of producing credible forecasts.

Models are suitable for such basic research type purposes because they have certain special attributes. First, models provide *insights* by integrating system parameters too numerous for the individual analyst to assimilate. Excessive attention to the plethora of data or to the multidigit accuracy that a computer can provide tends to both miss the message and mislead the user. Models should be designed for gaining insight and understanding, not (necessarily) for mathematical sophistication. The ability to formulate and computerize very large models today probably exceeds the ability to interpret the output and to understand the relevant policy implications. Such is characteristic of the formative stages of a new art or science.

A second desirable characteristic of computer modeling is that models can provide surprising and instructive *results* which should, then, be reproducible from basic logic; model results, once seen, should be obvious. Modeling does not, after all, replace careful thinking – it seeks to enhance it.

Thirdly, computer models are useful in that they provide *consistency* of calculation. For highly complex and quantitative subjects, modeling provides an essential accounting framework – a necessary classification scheme – to aid in the otherwise laborious if not impossible task of simultaneous calculations with hundreds or thousands of variables.

Finally, the formality of computer models or of the analytic frameworks is of high value for a particular reason. All policies and decisions are based on some implicit view of the future or a range of futures. The formal structure of models enables these assumptions to be explicit and subject to audit. This can serve as a defense against bias in decision making.

Recognizing these characteristics, the particular set of energy models at IIASA was conceived with perhaps four general objectives or goals in mind:

To study the long-term, dynamic (transitional), and strategic dimensions of regional and global energy systems; indeed, one cannot solve a problem until one understands it.

To explore the embedding of future energy systems and strategies into the economy, the environment, and society. Is there sufficient time and enough capital to achieve a given energy strategy?

To develop a global framework to enable the assessment of the global implications of long-term regional or national energy policies.

To evaluate alternative strategies – to compare options – of a physical and technological kind, including their economic impacts.

The energy models at IIASA have been developed with these goals in mind. The aim has been to organize and extend the debate on the impacts of future energy alternatives – to evaluate plausible energy strategies in a full systems context and to do so with a truly global perspective.

THE STRUCTURE OF THE SET OF ENERGY MODELS

Large monolithic computer models often suffer from overcomplexity and rigidity. Small and simple models offer relative clarity and understandability, while sacrificing (in many instances) methodological sophistication. Uncertain functional relationships in the first model type are replaced by uncertain human judgments in the second.

IIASA's energy modeling work has adopted elements of the latter approach – the linking of several relatively simple models into a coherent whole, an integrated set. In Figure 1 the model set is illustrated, and the most important (of many) linkages are shown. Here, only the general scheme and structure of the set as a whole is described. In the Appendixes, attention is given to each of the individual models.

The approach is, as apparent in Figure 1, a highly iterative one. Initiating assumptions and judgments lead to calculations and results that feed back and modify those assumptions and judgments. Most of the feedbacks are manual. Iteration here is meant to involve real and interactive human learning: an original assumption about the relative rate of penetration of liquid fuels into (or out of) residential markets (for example) would decrease (or increase) if relative fuel prices (stemming from supplies) showed a disadvantage for liquid fuels. While the flow of information is mechanized, the impacts of changes in one set of inputs on another are not. An example of the operation of the modeling loop and its several interactions is given in the last section of this report.

The energy modeling activity begins with scenario definitions (top of Figure 1). A scenario is a plausible future – a reasonable outcome of a set of reasonable assumptions. It is not a forecast; it is not a prediction. It is closer to a hypothesis.

In IIASA's energy research, two such scenarios are selected – two plausible futures believed to span a reasonable-to-expect range. They are defined by "high" and "low" economic growth within regions and consequent high and low energy demand growth. Population growth is also a scenario-defining parameter, although at present just one projection of population is used in IIASA's energy studies. Other factors vary from scenario to scenario according to judgments about internal consistency.

The scenarios, once defined in this way, do not remain inviolate. Feedbacks from the resulting energy calculations can, and do, modify original economic growth assumptions. At present this is done judgmentally. Formalization of the procedure depends on the availability and suitability of

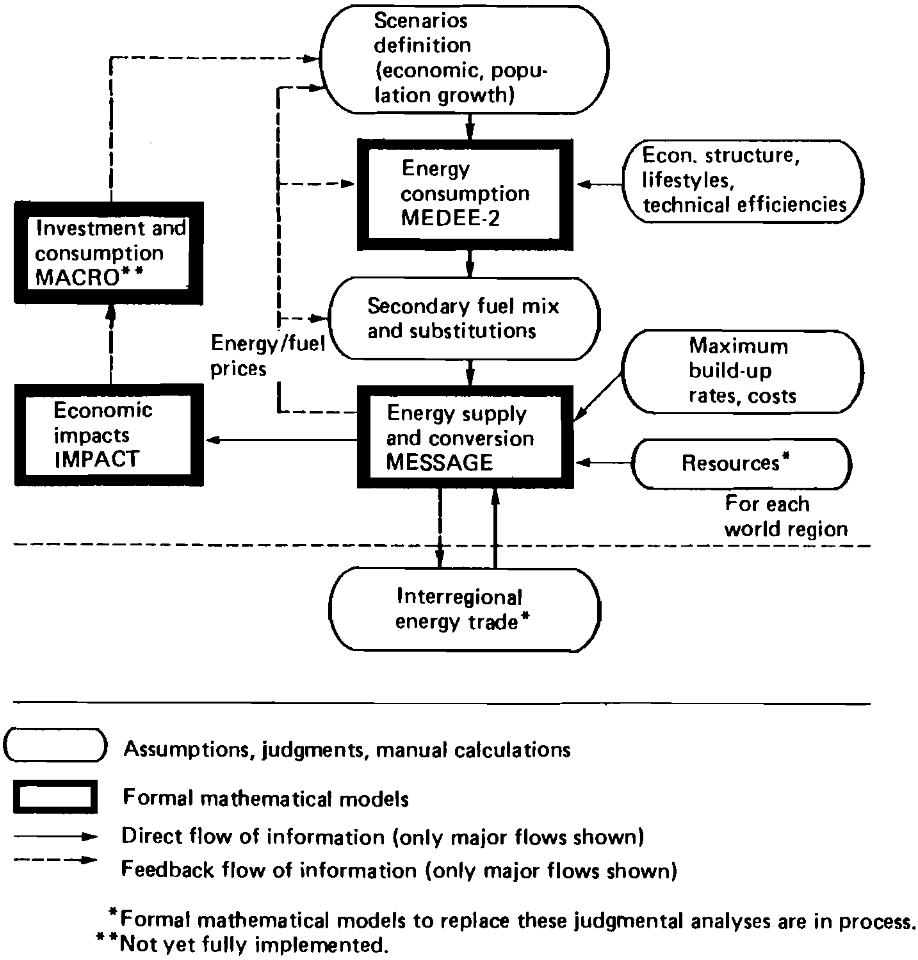


FIGURE 1 IIASA's set of energy models: a simplified representation.

modeling tools. (An example of how the process works at this time is described in a later section of this report.)

The scenario projections of economic and population growth for each world region provide the basic inputs for detailed calculations of future final energy consumption consistent with the scenarios. Disaggregation of these overall economic and demographic projections enables detailed consideration of economic and energy-consuming activities in three macro sectors: transportation, household/service, and industry (agriculture, construction, mining, and manufacturing). An array of judgments about lifestyle developments, improvements in efficiencies of energy-using devices, and the rate of penetration of new and/or improved energy-using equipment augment the disaggregated economic and demographic assumptions for each region. All of these details are meant to be consistent with the general scenario parameters and are recorded in a model called MEDEE-2* where calculations lead to estimates of useful and final energy consumption in the macro sectors. The requirements for activities such as direct heating, steam generation, space and water heating, and air conditioning are evaluated in terms of useful energy whereas those of nonstationary motive power, coke in pig-iron production and feedstocks in petrochemical industries are calculated directly in terms of final energy. Useful energy demand is also expressed as equivalent final energy following considerations of the penetration of soft solar, cogeneration, and heat pumps and anticipated changes in efficiencies of fossil fuels for different processes. The final energy thus obtained is partly in specific forms (motor fuel, coal for steam trains, coke, electricity, district heat, solar heat, feedstocks) and partly in a form allowing intersubstitution among coal, oil, and gas. The substitutable category can be – and is, in practice – allocated to various fossil fuels on the basis of price differentials obtained in previous iterations around the modeling loop.

The "Secondary Fuel Mix and Substitutions" box in Figure 1 represents this and other allocation judgments. There may be a great deal of flexibility in energy systems here. That is, it may be that a rigorous treatment of the possibilities for intersubstitution among competing fuels (and among energy and conceivable substitutes for energy like capital and/or labor) is warranted. This is a main objective of the ongoing modeling improvement work presently underway at IIASA. For the analyses described here, the limits of substitutability are best described as informed guesses. An example of the judgmental process is offered later in this report.

A further step takes into account transportation and distribution losses incurred in the supply of various forms of final energy as well as self-consumption of the energy sector. This step then completes the secondary energy demand calculations required as input to the energy supply and conversion model MESSAGE,† as shown in Figure 1.

MESSAGE calculates the required supplies of primary fuels to meet the secondary energy demands, at lowest cost and within sometimes quite tight constraints on resource availabilities, technological development, and the build-up rates of new energy facilities. Resource constraints are specified as maximum pools of oil, natural gas, coal, and uranium available at specified costs. As prices rise, several high cost alternatives can compete. Limits on the maximum build-up rate of energy facilities reflect the inherent lead times, as well as limitations on manpower, materials, etc., in a region.

Interregional energy trade considerations provide time profiles of imports and exports of fuels for each regional MESSAGE run. Relatively simple allocation rules distribute available exports of fuels (e.g., oil) from exporting

*MEDEE stands for *M*odele d'*E*volution de la *De*mande d'*E*nergie.
†MESSAGE stands for *M*odel for *E*nergy *S*upply *S*ystems *a*nd Their *G*eneral *E*nvironmental Impact.

regions (e.g., the Middle East and Northern Africa) to competing importing regions (e.g., Western Europe and Japan or Africa and South and Southeast Asia). Allocations are done iteratively with MESSAGE runs (Figure 1) so that a globally consistent balance is achieved.*

MESSAGE gives fuels production over time and the path of different primary fuels through conversion processes to a fixed set of secondary demands. In addition, MESSAGE provides the marginal production costs of primary fuels, leading to estimates of time trajectories of fuel and electricity prices. These prices are fed back (Figure 1) to several points in the loop, in order to iteratively modify initial assumptions and judgments.

To be specific, prices in this procedure affect three calculations. First, price changes alter macroeconomic growth patterns: increased prices can constrain overall growth and/or can shift activities from more- to less-energy-intensive sectors. These changes are made judgmentally at present, based on estimates made by experts inside and outside of IIASA.

Second, price changes alter lifestyles and technological efficiencies of energy-using devices. Such alterations can at best be informed guesses; as prices increase, efficiencies tend more toward the technical potentials and lifestyles adapt to lowered energy use. Assumptions are made clear and open, and the potential of energy savings from both categories are assessed at the maximum levels judged feasible. The specific measures that may be required to induce the lifestyle or the efficiency changes are not the emphasis here; the aim is rather to indicate the energy demand results if such lifestyle or efficiency projections were to occur.

Finally, relative price changes among different fuels and electricity can cause the mix of secondary energy types demanded to change; relative increases in liquid fuel prices induce shifts toward gaseous fuels, for example. No formal or precise elasticities of substitution are used here; again, best informed judgments describe the approach.

The new energy facilities required to meet the energy supply scenarios of MESSAGE have direct costs – capital, manpower, and materials costs. An IMPACT model (Figure 1) calculates the required direct and indirect (energy-related) costs of new energy facilities, and thus provides the basic information for assessing whether or not an economy can afford a given energy scenario. Exogenous assumptions about facility-specific size, material, and manpower requirements are made for IMPACT in order to calculate the direct and indirect requirements of a given energy strategy. In addition, a separate, detailed WELMM (*w*ater, *e*nergy, *l*and, *m*aterials, and *m*anpower) analysis, in the style of Grenon and Lapillone (1976), can be done following the IMPACT run.

With IMPACT-calculated costs, we can begin to ask whether energy will absorb unacceptably high shares of economic product. What forms of capital

*This procedure will be formalized through use of a gaming model in the near future. The gaming model originates with Alexej Makarov at the Siberian Power Institute. Alexander Papin is currently adapting it for use at IIASA.

and financial aid will be required by developing countries? What level of nonenergy exports are necessary to pay for large energy imports?

Finally, a MACROeconomic model (Figure 1) accepts exogenous assumptions about demographics and institutional parameters such as productivity, taxes, trade, etc., and calculates investment and consumption rates consistent with the costs from IMPACT. This allows assessment of the magnitude of change in, for example, the capital/output ratio if and when energy becomes increasingly capital intensive. This in turn enables a recheck of the original gross national product (GNP) estimates for each region and a reentering of the iterative process.

This last feedback is one toward which much of the energy modeling design and implementation work at IIASA has been leading. The critical question is

> Can economies *afford* the capital, or the time, to achieve energy strategies if, during the transition 15 to 50 years from now, energy becomes increasingly capital intensive?

It may be worthwhile to summarize the major inputs and outputs from the just-described structure of the IIASA energy modeling set. Figure 2 gives that summary.

The sectoral direct energy requirements as calculated in IMPACT provide (in theory at least) important inputs to the energy demand model (MEDEE-2)

A. ASSUMPTIONS AND JUDGMENTS, DYNAMICALLY, 1975–2030, FOR EACH WORLD REGION

- Demographics
- Economic growth
- Lifestyles
- Efficiencies of energy use
- Market penetrations, maximum build-up rates of new technologies
- Resource availabilities and costs
- Imports and exports
- Costs of facilities
- Institutional variables (e.g., productivity, capital—output)

B. OUTPUTS, DYNAMICALLY, 1975–2030, FOR EACH WORLD REGION

- Primary energy production, source mix
- Contributions of new technologies
- Electricity production by load region
- Shadow prices of fuels and electricity
- Environmental parameters
- Aggregate final energy demands
- Required capital investments
- Direct and indirect capital, manpower, and material requirements

FIGURE 2 Major inputs and outputs of the IIASA set of energy models.

for calculation of energy consumption by industrial sectors. For this purpose, implementation of an input–output INTERLINK* model is underway. INTERLINK would enable detailed industrial sectoral consistency between IMPACT results and the components of GNP for use in demand calculations in MEDEE-2.

This description has focused on the IIASA energy models as a set. Yet each model is different and each performs functions that have value independent of the set. The appendixes to this report give brief descriptions of several of the models, including general methodologies used, status, and certain central formulations of relationships.

THE SCOPE OF THE MODELS

The IIASA integrated set of energy models deals with a selection of the many important issues relating to energy. This, like any other model or set of models, is largely defined by system boundaries, which limit the scope of issues that can be treated. The model set *does*:

- *Describe the potential of a reasonable evolution of global and regional energy systems.* The intent, after all, is first to learn and understand the dynamics and inertia of large-scale energy systems.
- *Capture the long-term, slowly-changing macroeconomic characteristics of developed and developing economies.* A fuller understanding of the major interrelationships in energy systems is the primary aim.
- *Capture details, from other analyses, for integration into a comprehensive framework.* By putting the details into a common whole, relative contributions, effects, and potentials can be assessed.
- *Model the evolution of the energy supply, conversion, and distribution systems and, in so doing, incorporate resource, capital cost, environmental, and some political constraints.* Structural insights result from this capability.
- *Calculate the economic impact (capital, manpower, materials, etc.) of alternative strategies.* In doing this, we are enabled to evaluate whether or not an economy will be able to afford – in terms of time, capital, manpower, etc. – a given energy strategy.
- *Produce consistent scenarios on a global and world/regional level.*

At the same time, the model set does *not* deal with some issues. It even seeks to avoid them in order to increase its utility in the chosen areas. The model set does *not*:

- *Take into account most institutional, societal, and political issues.* Some such issues (e.g., political decisions which have the effect of setting a

*Not shown in Figure 1. See Propoi and Zimin (1979).

maximum level of annual US coal production) are considered and quantified; but for the most part the model set does not attempt to treat issues that are properly the concerns of others once the technical and economic information from the modeling is in hand. However, when issues of this kind must be included in the models, the assumptions are made clear and explicit.

- *Predict energy pricing policies, market fluctuations, interest rates, or multisectoral economic dynamics; or produce credible and detailed forecasts.* The models are long-term considerations of slowly-changing parameters; they offer no real aid to those who must carefully consider rapidly-changing variables whose periods are measured in months or a few years.
- *Treat technological details of small scale.* Similarly, the models do not attempt to consider in detail the many current and proposed technologies that may be important in micro terms but not, in our judgment, in macro terms. Wherever assumptions of this kind are relevant, they are clearly stated.
- *Simulate carefully the full nuclear fuel cycle or questions of safety or arms control.* These critical questions are receiving ample attention in many circles. It is not the attempt in our modeling exercise to enter that debate. Rather, the consequences of different courses of action are illustrated.
- *Evaluate the effects of specific tax, quota, regulatory, and financial incentive policies in detail.* The IIASA modeling set does not, for example, aim to evaluate the probable success or failure, the value or costs, of the specific policy proposals of the changing array of energy legislation in the United States. Such considerations are, in the frame of reference here, relatively short term – although not relatively unimportant.

A SELECTION OF ILLUSTRATIVE RESULTS: TWO GLOBAL SCENARIOS

The model set operates within a context defined by scenarios. Scenarios, as noted, are not forecasts but rather are plausible futures – reasonable outcomes from reasonable assumptions. Scenarios are quantitative representations of qualitative perceptions.

Two global energy scenarios for the next 50 years are examined here. This presentation is meant to be neither comprehensive nor exhaustive.* Rather, selected assumptions and results, selected descriptions of feedbacks, and judgmentally-based iterations of the modeling loops are meant to illustrate the operation of the IIASA set of energy models. The models, and the model results, are only as good as the exogenous assumptions that drive them.

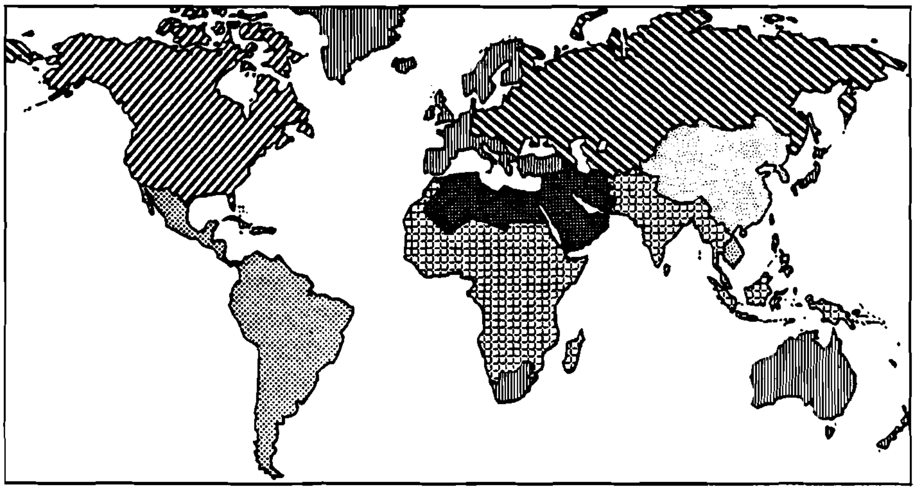
A Basis

Two items must be presented before launching into the scenario analyses: (1) the regional disaggregation of the world as used in the scenarios and (2) the energy situation at present (or, actually, in our Base Year 1975).

*The scenario assumptions and analytic results are reported comprehensively in Energy Systems Program Group of IIASA (1980).

Seven aggregate regions have been chosen for study. In some sense world regions are almost meaningless entities: the real decision-making bodies of the world are nations. Regions, or groups of nations, have exhibited little policy-setting strength to date. The aggregate character of a region may not match any single nation within it; regional groupings tend to mask important national characteristics. When necessary or suitable and possible, a region will be disaggregated in this study to subregions or nations.

The regions have been selected more for their economic and energy systems similarities than for geographical proximity. That is, one region is a developed market economy with large resources (Region I, NA), while another



Region I	(NA) North America
Region II	(SU/EE) The Soviet Union and Eastern Europe
Region III	(WE/JANZ) Western Europe, Japan, Australia, New Zealand, South Africa, and Israel
Region IV	(LA) Latin America
Region V	(Af/SEA) Africa (except Northern Africa and South Africa), South and Southeast Asia
Region VI	(ME/NAf) Middle East and Northern Africa
Region VII	(C/CPA) China and Centrally-Planned Asian Economies

FIGURE 3 The seven IIASA world regions.

is a developing economy with relatively few energy resources (Region V, Af/SEA), while another is a centrally-planned economy with large resources (Region II, SU/EE), and so on. Figure 3 shows each of the seven regions defined for these studies.

The present energy world has some important general characteristics. World primary energy consumption is just more than 8×10^{12} watt-years per year or, in short, 8 TWyr/yr on average. With the present world population of 4 billion, average per capita energy use is 2 kWyr/yr. But there are wide differences among nations. More than 70 percent of the world's population lives with less than 2 kWyr/yr/cap, and more than 80 countries have a consumption rate as low as 0.2 kWyr/yr/cap, while only 6 percent of the world enjoys more than 7 kWyr/yr/cap. Responsible technical planning must assume that the present uneven distribution will become less uneven, meaning that the global average will increase beyond 2 kWyr/yr/cap.

Table 1 contains the Base Year 1975 figures for commercial primary energy for the seven regions under study.

Scenario Definition

The iterative, interactive application of the energy models begins with the definition of two global scenarios: a High and a Low. Aggregate parameters are selected: economic growth and population growth. These are defined for each region, over time and for the period 1975–2030. For population growth, Professor Nathan Keyfitz of Harvard University has made a projection which is

TABLE 1 Commercial primary energy, Base Year 1975 (GWyr/yr).

Region	Solid	Liquid[a]	Natural Gas	Hydro[b]	Nuclear[b]	Total primary energy
I (NA)	484	1167	763	174	66	2654
II (SU/EE)	770	635	374	50	6	1835
III (WE/JANZ)	541	1252	238	180	45	2256
IV (LA)	16	228	48	45	1	338
V (Af/SEA)	119	159	20	29	1	328
VI (ME/NAf)	2	84	36	4	0	126
VII (C/CPA)	325	93	28	15	0	461
Total	2257	3618	1507	497	119	7998
Bunkers[c]						210
World						8208

[a]Including liquid fuels used as petrochemical feedstocks.
[b]Hydropower and nuclear power at primary equivalent.
[c]Bunkers include fuels used in international shipments of fuel.

used, unchanged, in both the High and Low scenarios (Keyfitz 1979). Figure 4 records this projection.

Economic growth is estimated for each region, based on published sources (e.g., WAES 1977 and WEC 1978), discussions with experts, and judgments about future resource constraints and interregional relationships. This estimation process leans on little methodology (as little is available), but it does rely on a few ground rules:

- WAES estimates are used for 1985; for 2000, they are modified slightly downward.
- WEC estimates are used as a "guide" for post-2000.
- General consistency is kept with US economic forecasts.
- For developing market economy regions, economic growth is generally linked to developed market economy regions; in particular, Region IV (LA) continues higher growth than that in Region V (Af/SEA), Region V (Af/SEA) is linked to developed regions' growth [about 1.5%/yr above Regions I (NA) and III (WE/JANZ), which are essentially member countries of the Organisation for Economic Co-operation and Development (OECD)], and Region VI (ME/NA) is loosely linked to developed regions (about 2.0%/yr above OECD).

The economic growth estimates, High and Low, that result from this process are not inviolate. Indeed, as energy prices and interregional energy trade

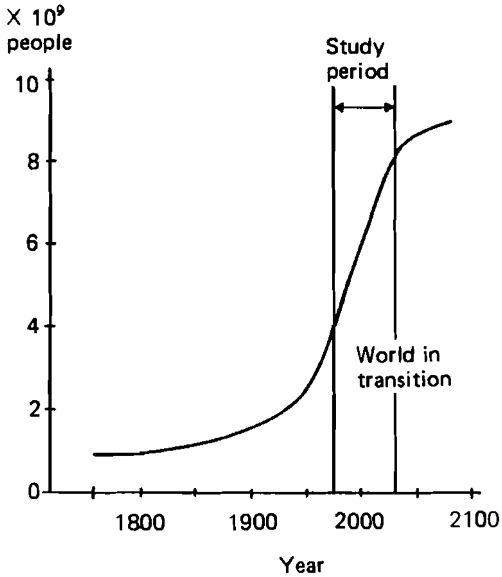


FIGURE 4 World population projections to 2030. Based on data from Keyfitz (1979).

patterns emerge late in the analyses, original estimates are modified – judgmentally. After several iterations, the economic growth figures summarized in Table 2 result.

One might question the use of simply gross domestic product (GDP) to distinguish scenarios. Indeed, it may be that there are more similarities than differences between the High and Low scenarios – because, really, societal and economic *structural* changes produce wider variations among scenarios

TABLE 2 Historical and projected growth rates of GDP, by Region, High and Low scenarios (%/yr).

A. High scenario

	Historical		Scenario projection			
Region	1950–1960	1960–1975	1975–1985	1985–2000	2000–2015	2015–2030
I (NA)	3.3	3.4	4.3	3.3	2.4	2.0
II (SU/EE)	10.4	6.5	5.0	4.0	3.5	3.5
III (WE/JANZ)	5.0	5.2	4.3	3.4	2.5	2.0
IV (LA)	5.0	6.1	6.2	4.9	3.7	3.3
V (Af/SEA)	3.9	5.5	5.8	4.8	3.8	3.4
VI (ME/NAf)	7.0	9.8	7.2	5.9	4.2	3.8
VII (C/CPA)	8.0	6.1	5.0	4.0	3.5	3.0
World	5.0	5.0	4.7	3.8	3.0	2.7
I + III[a]	4.2	4.4	4.3	3.4	2.5	2.0
IV + V + VI[a]	4.7	6.5	6.3	5.1	3.9	3.5

B. Low scenario

	Historical		Scenario projection			
Region	1950–1960	1960–1975	1975–1985	1985–2000	2000–2015	2015–2030
I (NA)	3.3	3.4	3.1	2.0	1.1	1.0
II (SU/EE)	10.4	6.5	4.5	3.5	2.5	2.0
III (WE/JANZ)	5.0	5.2	3.2	2.1	1.5	1.2
IV (LA)	5.0	6.1	4.7	3.6	3.0	3.0
V (Af/SEA)	3.9	5.5	4.8	3.6	2.8	2.4
VI (ME/NAf)	7.0	9.8	5.6	4.6	2.7	2.1
VII (C/CPA)	8.0	6.1	3.3	3.0	2.5	2.0
World	5.0	5.0	3.6	2.7	1.9	1.7
I + III[a]	4.2	4.4	3.1	2.1	1.3	1.1
IV + V + VI[a]	4.7	6.5	5.0	3.8	2.9	2.6

[a]Presented for purposes of comparison with data of WAES (1977) and of other global studies which exclude centrally-planned economies.

NOTE: Historical and projected values of GDP in constant (1975) US dollars are given in Chant (1979).

than do simple levels of GDP. Regrettably, such scenario types are difficult to deal with, and their specification may well be inconsistent with the model structure. In any case, we believe that much can be learned from our scenario choice. And we *have* explored other, more widely varying scenarios as described in Energy Systems Program Group of IIASA (1980).

Secondary Energy Demand and Fuel Mix Calculations

From the economic and population growth estimates that define the scenarios, estimates can be made of the sectoral breakdown of the gross regional product and of the urban–rural distribution of the population. The former is based on general considerations of the pace and trends of economic development in a region (e.g., trends toward more services and less agriculture or toward more heavy manufacturing) and on runs of the MACRO model if suitable data are available to support such analyses. This procedure can surely be improved, and expansions of MACRO are now in progress to this end.

Population distribution projections are based on published sources for Base Year 1975 and extrapolation of urbanization or de-urbanization trends.

Disaggregation of gross regional product and population distribution over time are MEDEE-2 model inputs. Also input are estimates of detailed economic (energy-using) activities, changes in energy-use efficiencies, several lifestyle parameters, and the rate of penetration of electricity, district heat, and distributed solar heating and cooling systems into domestic and industrial markets. All of these are judgments – best estimates felt (by the members of the modeling group and by consulted outside experts) to represent reasonable consistency within the general character of the scenario for each region. The initial estimates are often revised in the iteration process as relative fuel supplies and prices and trade-offs of domestic/imported fuels in each region lead one to re-estimate them. No formal mechanism exists for such iteration; we believe, frankly, that informed judgment may be at least as reliable as mathematical representation in such matters. (Two examples of this process: higher than expected liquid fuel prices in a region might lead to an increase in an original estimate of automobile fuel efficiency and a decrease in an original estimate of total automobile kilometers traveled, or they might hasten a shift to noncar modes of transportation. High electricity prices might lead to a lowering of the electricity penetration into heat markets.)

MEDEE-2 uses the inputs mentioned in the previous paragraph to calculate, ultimately, final energy in two forms: specific uses (e.g., motor fuel, coke, feedstocks, electricity, district heat, soft solar) and substitutable fossil fuels for heat. The latter are disaggregated manually for the domestic and industrial sectors, separately.

The decision process here differs for different regions, but many common elements exist. For example, if the marginal production costs (a MESSAGE output) for liquid fuels rise higher and faster than for gas, as is the case in nearly every region, then substitutable fossil uses are shifted from liquid fuels to gas. Shifts from one source to another also incorporate estimates of built-in lead times for such changes, the potentials for coal in industry and lack of desirability (generally) for coal use in residences, and local and regional situations that (e.g., by access to local, relatively inexpensive heating oil) prevent 100 percent coverage of a market by any particular fuel.

After some iterations, the mix of secondary fuels demanded (a fixed input to MESSAGE) is consistent with the pattern of prices stemming from the supply analyses for each region and scenario. The secondary energy demands for the High scenario are reported in Figure 5.

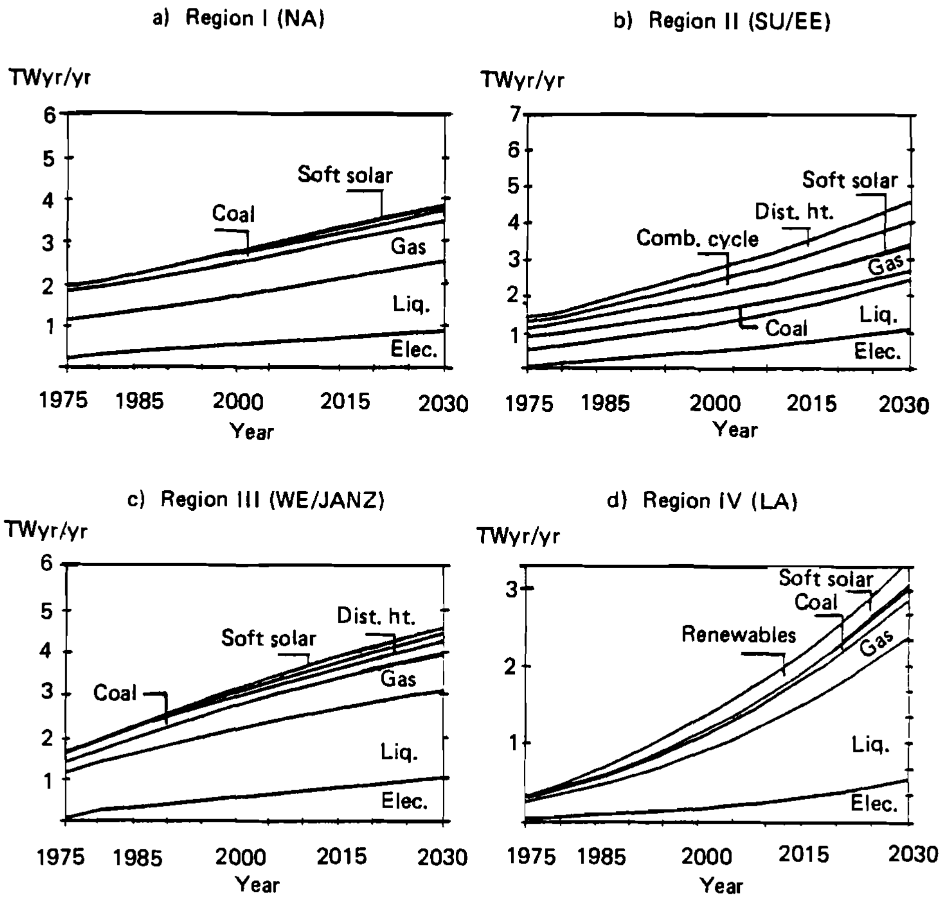


FIGURE 5 Secondary energy demand, High scenario, 1975–2030.

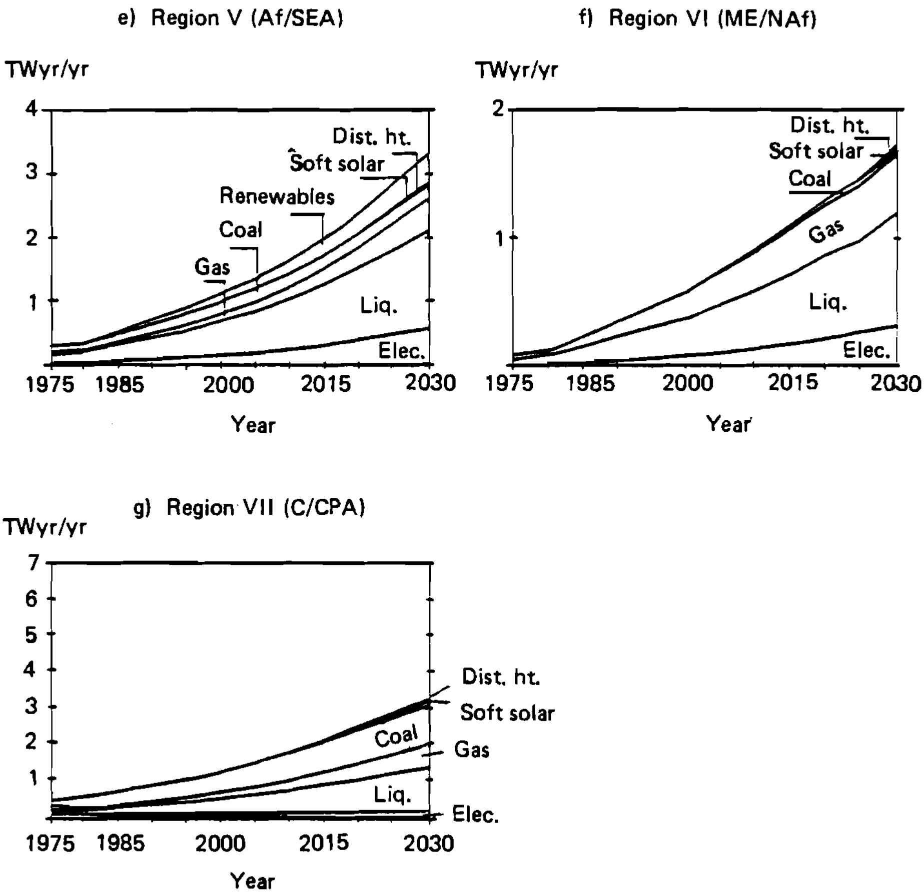


FIGURE 5 *Continued.*

Energy Supply and Conversion and Energy Trade Calculations

The energy supply system is modeled by the dynamic linear programming MESSAGE model. Exogenous inputs for each region (and scenario) include the secondary energy demands of Figure 5, estimates of capital and operating costs for energy conversion facilities, constraints on the initial start-up dates and maximum build-up rates of new energy supply and conversion technologies, maximum annual production rate specifications for some resources (in some regions), and, at present, maximum allowed annual imports or exports of specific fuels. These inputs come from a variety of sources: demands from MEDEE-2 as described; costs from available published sources (per unit capital costs are, for simplicity and reflecting basic uncertainties, held constant in real terms over the planning horizon); maximum build-up rates from IIASA Energy

Systems Program's "market penetration" analyses; and production rates and imports/exports from iterative analyses described below.

Calculation of maximum annual production rate constraints for each region begins with estimates of the amount of each kind of resource (i.e., of oil and coal; gas production is left unconstrained because gas is found to be market-limited, not production-limited) available at different price levels.* For coal, annual production ceilings represent the aggregate of considerations of limits in transport, manpower, water availability, location of deep-water ports, etc. Such ceilings are imposed in the major coal-bearing regions – I (NA), II (SU/EE), III (WE/JANZ), V (Af/SEA), and VII (C/CPA). Since these coal constraints are often binding in the scenario analyses, they are summarized here in Table 3. The values selected are judged to represent high, but achievable production levels, given the general considerations already noted.

TABLE 3 Coal maximum production rate assumptions, High scenario [maximum annual production constraint (GWyr/yr)[a]].

Region	Base year 1975	Year 1985	2000	2015	2030
I[b] (NA)	559	900	1500	2000	2700
II[c] (SU/EE)	807	1300	2400	3000	3500
III (WE/JANZ)	466	600	800	1000	1000
V (Af/SEA)	116	225	450	825	1315
VII (C/CPA)	325	800	1500	2000	3500

[a] 1 GWyr/yr = 1.08×10^6 tce/yr.
[b] To reach 2700 GW by 2020.
[c] Figures given are for the High scenario; Low scenario limits, from 1985 to 2030, are 1600, 2600, 2900, and 3000.
Note: These constraints represent the roughly-assessed composite and aggregate limitations of water, manpower, transport, environmental safeguarding, etc., in each region.

For oil, assumptions about discovery rates, the contributions of enhanced recovery, unconventional sources, etc., lead to projections of *technical potential* production. These projections are then modified by observing liquid fuel demands and the relative marginal cost increases among regions until an oil production profile for each region is achieved. Clearly, analysis of oil imports/exports must enter (iteratively) here.

The oil trade pattern in the scenarios results from the following considerations.

*These estimates are provided by the IIASA Resources Group under the leadership of Michel Grenon; they are reported in the chapter on fossil energy resources in Energy Systems Program Group of IIASA (1980).

Three dynamic elements of the world oil market must be assessed in any study of global, long-term energy supply systems: regional domestic oil production, interregional oil trade, and oil prices. The procedure shown in Figure 6 allows such assessment.

Taking estimates of potential oil production and assuming some dynamics of interregional oil price, the economic portion of potential production is assessed. These price-consistent oil production curves (Figure 7) when compared with liquid fuel demands region by region, produce values for interregional oil trade over time. These values are input to the MESSAGE model.

Analysis of MESSAGE outputs, taking account of each region's maximum potential oil production, gives curves, period by period, for oil imports (exports) as a function of price. Region VI (ME/NA) is an exception for which the maximum available exports of oil over time are calculated as the difference between its assumed production ceiling and its domestic liquid fuel demand.

The regional curves of oil imports versus price for each period of time are then aggregated into a global one. On this curve, one finds a value of imports

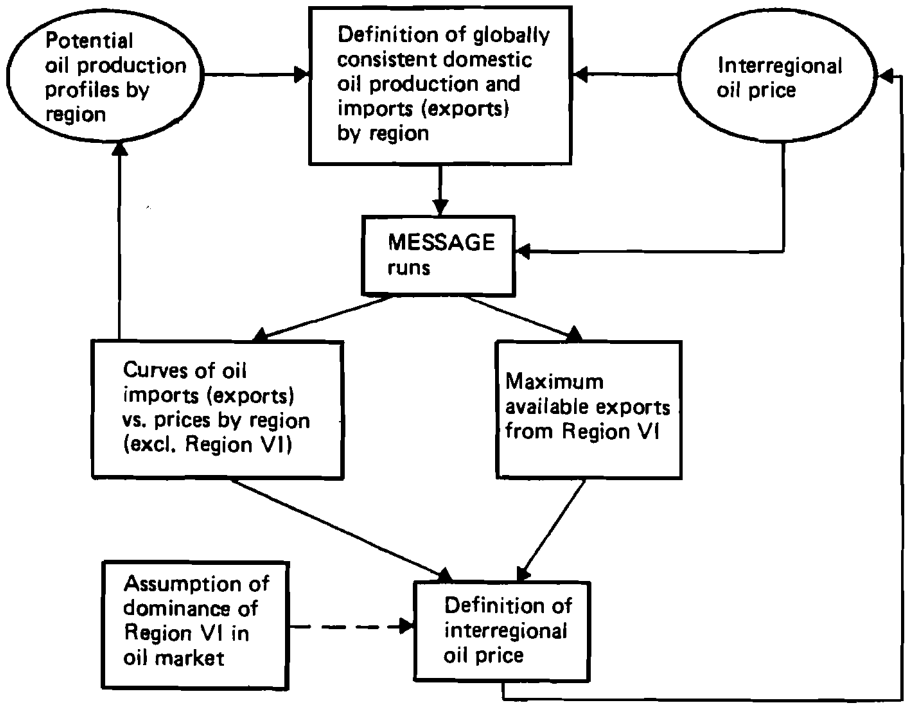
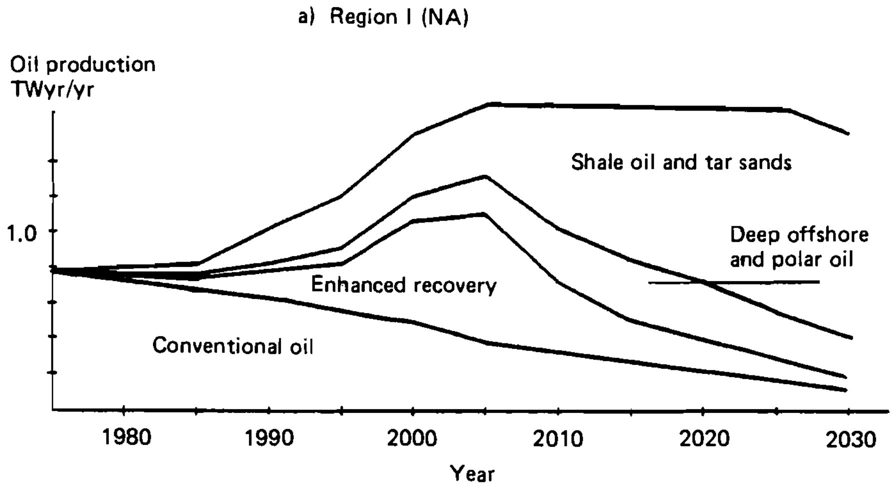


FIGURE 6 Interregional oil balancing methodology.



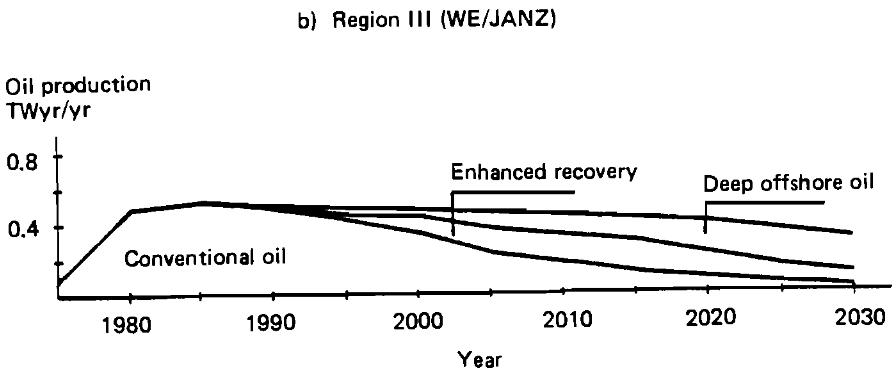
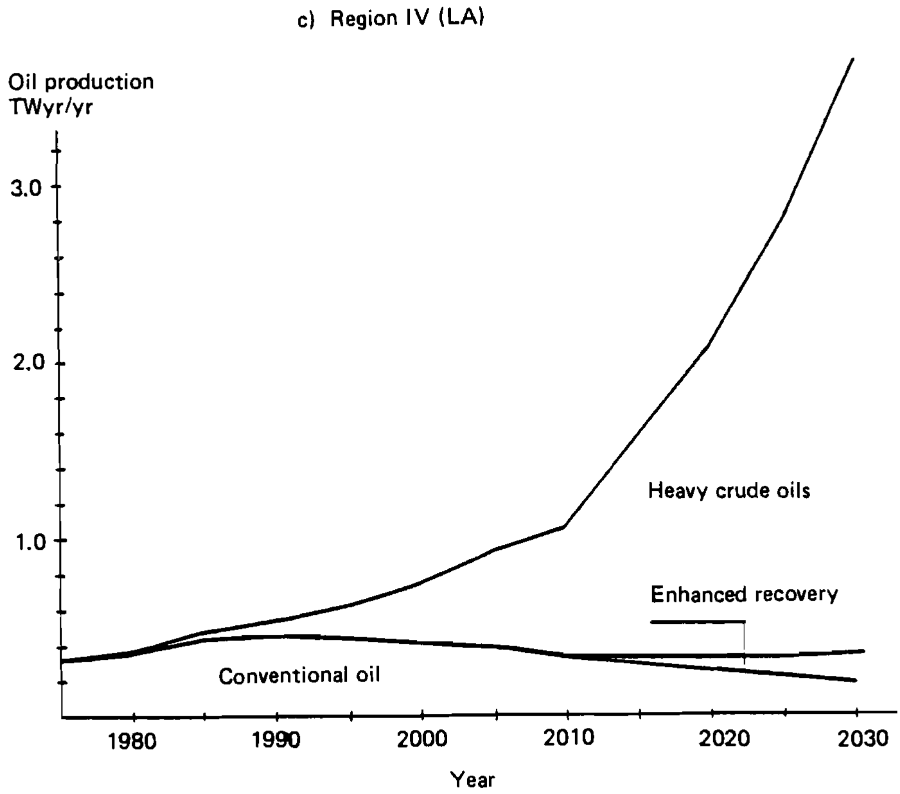


FIGURE 7 Maximum potential production profiles by type of oil, Regions I, III, IV, and V.



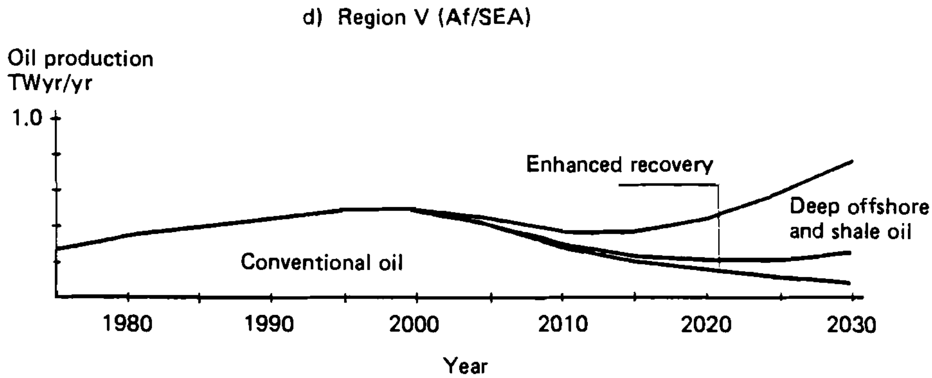


FIGURE 7 *Continued.*

that can be satisfied by Region VI (ME/NA) (within its assumed oil production ceiling) and that maximizes its net oil revenues.

The top graph in Figure 8 shows the total imports demanded at different oil price levels in the Low scenario in the year 2015. Fewer imports are required as prices rise, and domestic substitutes become economic. The lower graph in Figure 8 shows the revenues accruing to Region VI at various levels. The assumed Region VI production ceiling of 33.6 million barrels per day does *not*

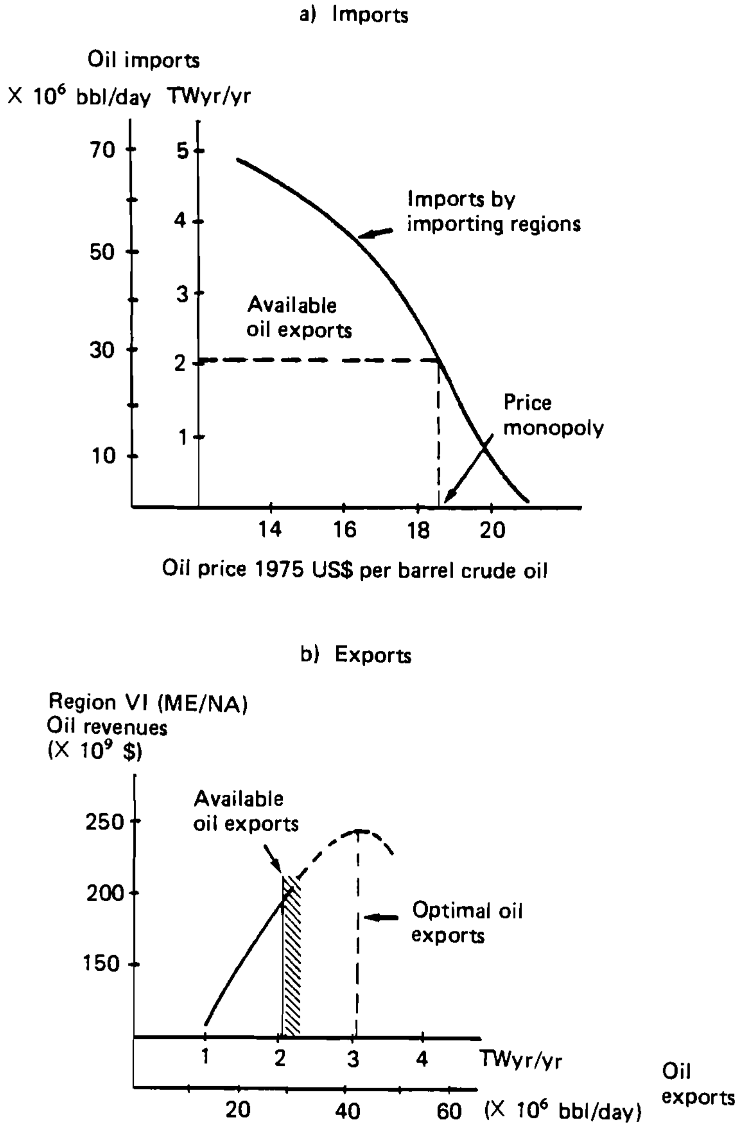


FIGURE 8 Oil imports and exports versus price, Low scenario, 2015.

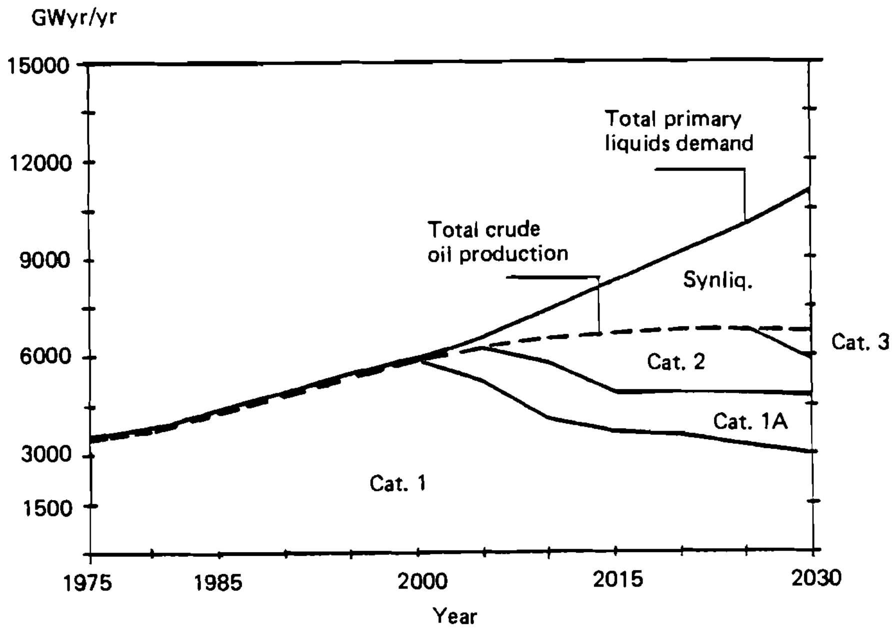
give maximum revenues in 2015. However, it seems at least plausible that Region VI will neither require nor desire more revenues than those resulting from the assumed production ceiling.

Several iterations of this procedure are required for acceptable results – to remove inconsistencies among oil demand, production, and import/export. Also, it should be noted that this procedure is designed for long-term analyses. It is assumed that the next few years will see oil supplies growing to equal demand, without *major* upward pressure on prices.

Once these several inputs and constraints are set, MESSAGE operates (for each region and scenario) as a cost-minimizing dynamic linear program. The resulting mix of primary supply sources and conversion technologies represents the minimum total discounted cost possible to meet the fixed (within MESSAGE) secondary energy demands *within the specified constraints*. Actually, the cost-minimizing process in MESSAGE generates much less of the character of the results than do the exogenously specified constraints. The MESSAGE runs are, in short, relatively tightly constrained.

MESSAGE outputs are rich in substance. Primary energy by source; electricity by generating technology; liquid, gaseous, and solid fuel supplies by source; product costs for secondary energy forms; marginal costs and other valuable indicators of the character of energy supply scenarios all result from MESSAGE runs. Figures 9 and 10 show a few sample plots from MESSAGE.

a) High scenario



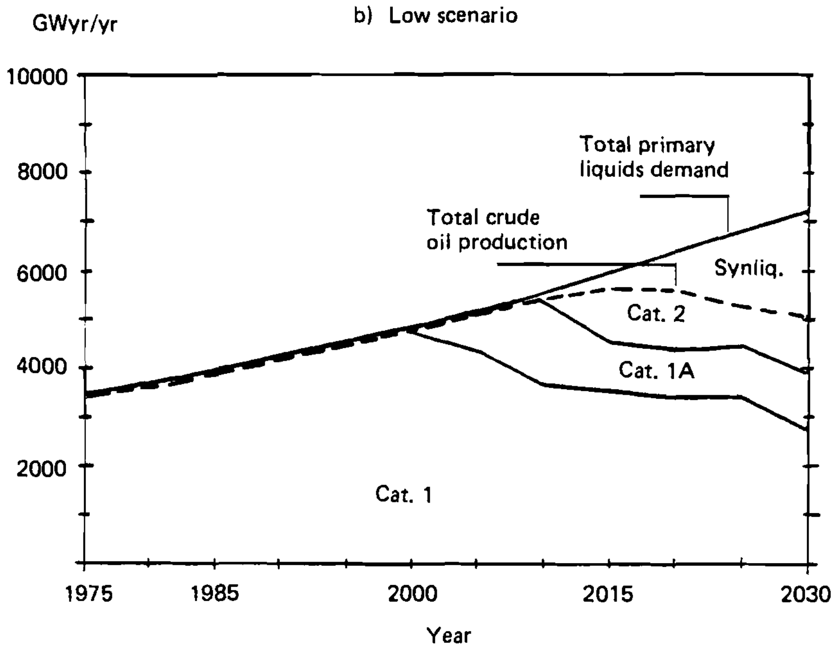


FIGURE 9 Global oil supply and demand, 1975–2030, High and Low scenarios, crude oil equivalent. Categories represent estimates of costs either at or below the stated volume of recoverable resources (in constant 1975 US$). For oil and natural gas, Cat. 1: 12$/boe (barrels of oil equivalent); Cat. 2: 12–20$/boe; Cat. 3: 20–25$/boe. For coal, Cat. 1: 25$/tce (tons of coal equivalent); Cat. 2: 25–50$/tce. For uranium, Cat. 1: 80$/kgU; Cat. 2: 80–130$/kgU. A subcategory of oil, 1A, exists only for Regions I (NA) and IV (LA) and includes oil available at production costs of $12 –16/boe. Also, a subcategory of gas, O, exists only for Region VI (ME/NAf), with gas available at $2/boe.

The point, as noted earlier, is not to elaborate here on the scenarios, but rather to illustrate the method of analysis. (Global results are shown here. In fact, MESSAGE is run for a single region at a time and the results can then be summed to the world.)

Economic Impact Calculations

From evaluations of the energy supply system in MESSAGE come required annual energy sector capacity additions, by primary energy production or conversion technology type. Given per unit capital costs of such facilities, the IMPACT model can calculate the associated investments for each energy scenario.

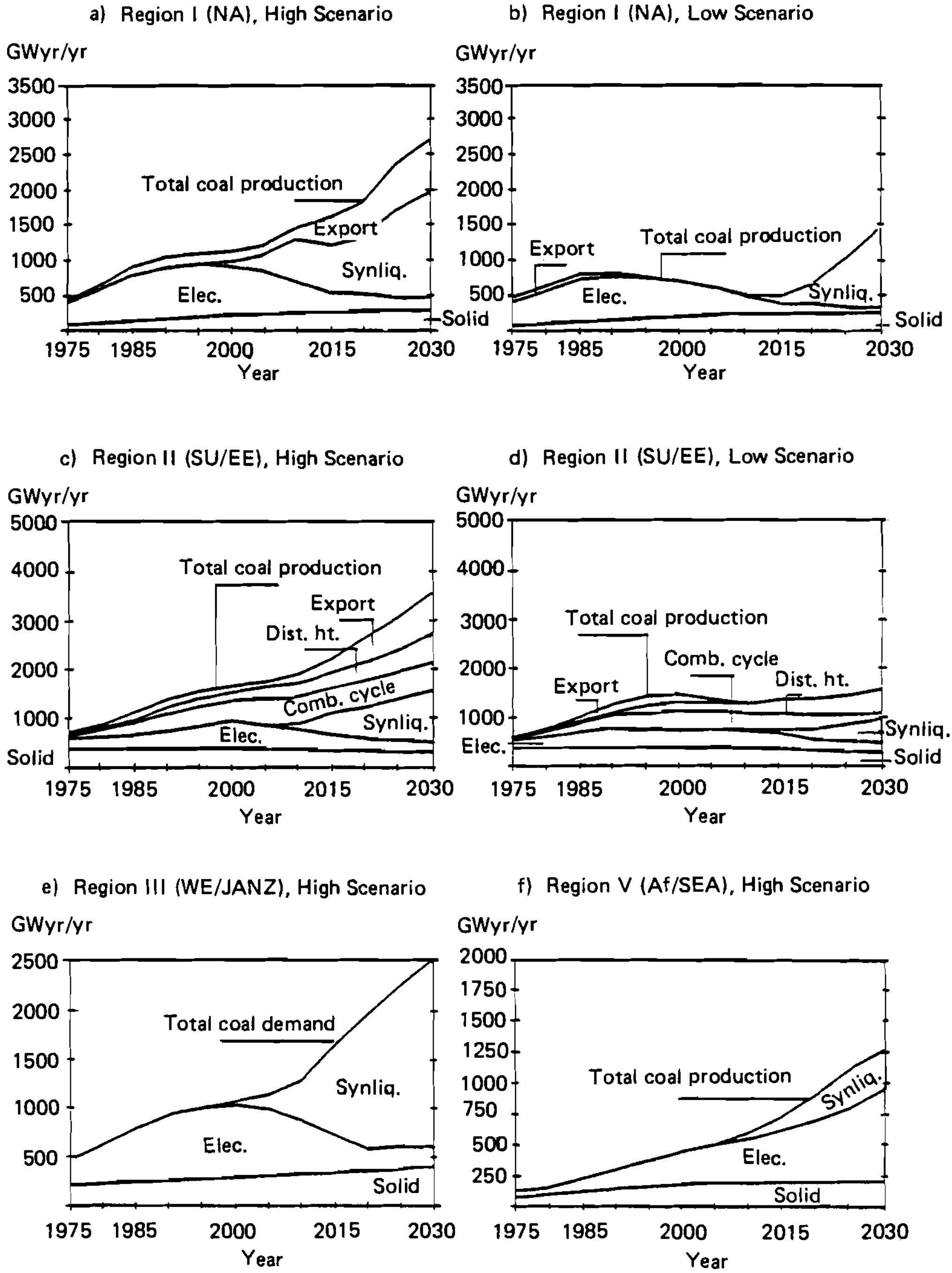


FIGURE 10 Coal supply and demand for Regions I, II, III, and V, 1975–2030.

IMPACT is input–output in structure. The main exogenous inputs required are coefficients relating the energy sector to other productive sectors of the economy and the facility size, capital cost, and material and manpower requirements. These inputs are drawn primarily from published sources, mostly from the Bechtel Energy Supply and Planning Model data base (Bechtel 1975).

IMPACT generates, for each region and scenario:

- Direct investments in required energy supply technologies,
- Required capacity additions in related branches of industry and corresponding (indirect) capital investments,
- Requirements of materials, equipment, and services in energy sectors, and
- Direct and indirect WELMM* requirements

These IMPACT results offer at least two as-yet unused feedback possibilities. First, as shown in Figure 1, a calculation of the potential dampening effect of high energy-investment requirements on the macroeconomy could be made. This requires a careful linking of IMPACT and MACRO (in process) and an ability to translate, for a region, the *kind* of macroeconomic changes that result from, for example, an increased capital–output ratio stemming from increased capital intensiveness of the energy sector. A second feedback possibility uses the industrial sector output changes (due to the energy supply scenarios) for changing industrial energy demands calculated in MEDEE-2.

An Example of the Iterative Process: The Case of Region III (WE/JANZ)

Much has been made in this paper of the iterative process of analysis inherent in the modeling loop of Figure 1. The preceding section attempted to shed some light on this process through an example of model application for two global scenarios. In this section, a further underlining of the iterative process makes use of a brief case example (Region III, WE/JANZ).

Attention is given here to two possible alterations of initial assumptions (there are others): changes in the secondary energy shares and changes in relative rates of penetration of alternative final energy types. These two feedbacks are shown in Figure 1.

Table 4 shows the changes in the mix of secondary energy shares (of "substitutable fossil" uses) based on the energy price trajectories from MESSAGE runs. Initially (for example), the gaseous fuels share of fossil sources of heat in residences and commercial buildings was assumed (in the High scenario) to reach 60 percent by 2030. Because of the relative price rise of oil

*WELMM stands for *w*ater, *e*nergy, *l*and, *m*aterials, and *m*anpower. It is a special data base technique developed at IIASA (see Grenon and Lapillonne 1976).

TABLE 4 The iterative process, example 1: assumed secondary energy shares, changes in Region III (WE/JANZ), High scenario (%).

(a) First estimates

	Base Year 1975	2000	2030
Industry "Substit. Fossil"			
oil	53.0	50	40
gas	35.1	35	40
coal	11.9	15	20
Household/Service "Substit. Fossil"			
oil	65.2	65	38
gas	22.9	30	60
coal	11.6	5	2

(b) Final estimates (after iterations based on relative price movements)

	Base Year 1975	2000	2030
Industry "Substit. Fossil"			
oil	53.0	35	20
gas	35.1	50	60
coal	11.9	15	20
Household/Service "Substit. Fossil"			
oil	65.2	55	28
gas	22.9	40	70
coal	11.6	5	2

and the somewhat surprisingly flat price trajectory for natural gas, the gas share has been increased for the residential and commercial sector to 70 percent by 2030; similar increases have been made for the industrial sector, particularly by the year 2000. This, clearly, is highly judgmental, and mostly arbitrary. It reflects the possible rate of growth of different markets, pushed to feasible limits, in this case in the direction of more gas use. This one change would result in 188 GWyr/yr less oil, and more gas, used in 2030 in this region, for the High scenario.

A second iteration, based on relative energy price movements, was a change in the assumed rate of penetration of electricity into heat markets in Region III (WE/JANZ). This, one of the many exogenous inputs to the MEDEE-2 model, was reduced after successive iterations revealed the tight supply situation for electricity and, in particular, the pressure on coal as a source of both electricity and essential liquid fuels. It was clear that if electric uses in WE/JANZ could, in general, be substituted by gas, aggregate prices

TABLE 5 The iterative process, example 2: assumed electricity penetration, Changes in Region III (WE/JANZ).

(a) First estimates

	1975 a normalized base	High scenario 2000	High scenario 2030
Industrial process heat (GWyr/yr)	*268*	*524*	*751*
electric, resistive (%)	0	7	15
electric, heat pump (COP = 2) (%)	0	0	0
Household/service space heat (GWyr/yr)	*204*	*390*	*490*
electric, resistive (%)	4	11	18
electric, heat pump (COP = 2) (%)	0	1	2
Electricity used for heat (GWyr/yr)	8	81	207

(b) Final estimates (after iterations based on relative price movements)

	1975 a normalized base	High scenario 2000	High scenario 2030
Industrial process heat (GWyr/yr)	*268*	*513*	*743*
electric, resistive (%)	0	3	4
electric, heat pump (COP = 2) (%)	0	0	1
Household/service space heat (GWyr/yr)	*204*	*319*	*374*
electric, resistive (%)	4	5	5
electric, heat pump (COP = 2) (%)	0	3	5
Electricity used for heat (GWyr/yr)	8	36	61

would be lower, domestic coal would be able to meet a higher share of liquid fuel needs, and total energy imports would be lower. Since several items are generally changed during any one iteration, it is not possible to quantify precisely the impacts of any single change; Table 5 summarizes, however, the changes in electrification assumptions in the iterative process and the resulting (approximate) change in total electricity consumption.

Of course, MESSAGE results serve, iteratively, to modify other assumptions and judgments. As oil prices rise more rapidly than originally expected, for example, domestic crude oil production increases, and imports or perhaps the use of expensive oil alternatives decline. The aim of the process is to reach a consistent picture of future energy prospects, such as outlined in the two global scenarios of the preceding section and as presented more fully in Energy Systems Program Group of IIASA (1980).

ONGOING WORK

Energy modeling work at IIASA does not stop here. The general perspectives gained through these analyses lead to the need for a more thorough investigation of the economic impacts of future energy paths and of the abilities of both developed and developing nations to deal with such impacts. In the future modeling efforts of IIASA's Energy Systems Program, two objectives will be sought: an understanding of the effect on domestic economies of energy sector capital (and material and manpower) requirements and an understanding of the effect on world trade and national or regional balance of payments constraints of high-cost energy. That is, what levels of capital flows and financial aid must accompany energy scenarios for the next 5 decades? Will balance of payments constraints be violated? Will developing countries receive the requisite aid and foreign investment for their energy growth?

IIASA's energy modeling approach, now operational to the point of generating detailed energy demand and supply scenarios, was conceived and designed with these questions in mind. The challenge now is to continue – to expand the energy modeling work to these fundamental international economic issues, and to therefore better assess the real energy-related limits and opportunities for the future of the globe.

REFERENCES AND BIBLIOGRAPHY

Agnew, M., L. Schrattenholzer, and A. Voss. 1979. A Model for Energy Supply Systems Alternatives and Their General Environmental Impact. WP-79-6. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Bechtel Corporation. 1975. The Energy Supply Planning Model. Final Report to the National Science Foundation. NSF-C867. San Francisco, California.

Chant, V.G. 1979. Two Global Scenarios: Evolution of Energy Use and the Economy to 2030. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Chateau, B., and B. Lapillonne. 1977. La Precision a long Terme de la Demande d'Energie. (The Long Term Forecast for Energy Demand). Paris: National Center for Scientific Research (CNRS).

Energy Systems Program Group of IIASA. 1980. Energy in a Finite World: A Global Energy Systems Analysis. Laxenburg, Austria: International Institute for Applied Systems Analysis (forthcoming in 1981 with Ballinger, Cambridge, Massachusetts).

Grenon, M., and B. Lapillonne. 1976. The WELMM Approach to Energy Strategies and Options. RR-76-19. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Häfele, W., and A. Makarov. 1977. Modeling of Medium- and Long-Range Energy Strategies. Discussion paper, Conception and Embedding, Workshop on Energy Strategies, May 1977. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Häfele, W., and A.S. Manne. 1974. Strategies for a Transition from Fossil to Nuclear Fuels. RR-74-7. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Keyfitz, N. 1979. Population of the World and Its Regions, 1975–2050. WP-79-119. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Kononov, Yu., and A. Por. 1979. The Economic Impact Model. RR-79-8. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Lapillonne, B. 1978. MEDEE-2, A Model for Long-Term Energy Demand Evaluation. RR-78-17. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Parikh, J. K., and K. S. Parikh. 1978. Simulation of Macroeconomic Scenarios to Assess the Energy Demand for India (SIMA). RR-79-15. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Propoi, A., and I. Zimin. 1979. Energy Resources: Economy Development Models. WP-79-2. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Rogner, H.-H. 1980. MACRO: A Macroeconomic Module for the IIASA Set of Energy Models. Laxenburg, Austria: International Institute for Applied Systems Analysis (forthcoming).

Workshop on Alternative Energy Strategies (WAES). 1977. Energy: Global Prospects, 1985–2000. Report of the Workshop on Alternative Energy Strategies. New York: McGraw-Hill.

World Energy Conference (WEC). 1978. World Energy Resources 1985–2020: Executive Summaries of Reports on Resources, Conservation and Demand to the Conservation Commission of the World Energy Conference. Guildford, UK: IPC Press.

Appendixes

DESCRIPTION OF INDIVIDUAL MODELS

The appendixes describe the underlying logic and structure of several of the models in the IIASA set of energy models.

APPENDIX A: THE MEDEE-2 MODEL

ALOIS HÖLZL

The MEDEE-2* model is a simplified version of a more general approach for assessing the long-term evolution of energy demand, an approach developed by Bertrand Chateau and Bruno Lapillone at the Institute of Energy Economics and Law (IEJE), University of Grenoble, and implemented at the International Institute for Applied Systems Analysis (IIASA) by Bruno Lapillone. Since 1979 the model has been operated at IIASA by Alois Hölzl and Arshad Khan. MEDEE-2 is a simulation model for calculating the useful† and/or final energy demand of major end-use categories such as space heating/cooling, water heating, and cooking in the residential and service sectors or space/water heating, steam generation, and furnace operation, in industry, based on exogenous assumptions about the long-term evolution of the main determinants of each of these energy-using activities.

MACROECONOMIC INDICATORS

Gross domestic product (GDP) formation by type of economic activity is required for the energy demand calculations. The following sectors are distinguished in MEDEE-2:

• agriculture	(ISIC 1)
• mining	(ISIC 2)
• manufacturing	(ISIC 3)
basic materials	(ISIC 34–37)
machinery and equipment	(ISIC 38)
food and textiles, and miscellaneous industries	(ISIC 31–33, 39)

*The acronym MEDEE stands for *M*odele d'*E*volution de la *D*emande d'*E*nergie.

†If a substitution between various energy forms in a given market is unlikely, the calculations are done in terms of final energy only. The term "useful energy" should be interpreted as the amount of electricity required for a given service.

- electricity/gas/water (ISIC 4)
- construction (ISIC 5)
- services (ISIC 6)

Desirably, energy-related activities in the mining and manufacturing sectors should be broken down to avoid double-counting of energy consumption of conversion sectors. Sometimes, however, a lack of statistics does not permit these activities to be treated separately.

The GDP share of each sector can be specified exogenously. Alternatively, they can be calculated from econometric equations in the model, based on assumptions about GDP expenditure. In the latter case, the following equations are used.

$$YAG = c_1 + c_2 \cdot Y \tag{A1}$$
$$YMIN = c_1 + c_2 \cdot YMAN \tag{A2}$$
$$YMAN = c_1 + c_2 \cdot GCF + c_3 * (TPCDG + TPCNDG) \tag{A3}$$
$$YEN = c_1 + c_2 \cdot Y \tag{A4}$$
$$YB = c_1 + c_2 \cdot GCFB \tag{A5}$$
$$YSER = c_1 + c_2 \cdot TPCSER \tag{A6}$$
$$VAMAN = c_1 + c_2 \cdot YMAN \tag{A7}$$
$$VAIG = c_1 + c_2 \cdot YB + c_3 * VAM + c_4 * VAC \tag{A8}$$
$$VAM = c_1 + c_2 \cdot GCFM + c_3 * TPCDG \tag{A9}$$
$$VAC = c_1 + c_2 \cdot TPCNDG \tag{A10}$$
$$VAMIS = c_1 + c_2 \cdot Y \tag{A11}$$

where

Y, YAG, $YMIN$, $YMAN$, YEN, YB, $YSER$ denote total GDP and GDP contribution by sector (agriculture, mining, manufacturing, electricity/gas/water, construction, and services, respectively)

$VAMAN$, $VAIG$, VAM, VAC, $VAMIS$ denote total value added by manufacturing industries and value added by subsector (basic materials, machinery and equipment, food and textiles, miscellaneous, respectively)

GCF, $GCFB$, $GCFM$ denote total gross capital formation and gross capital formation in buildings and in machinery/equipment, respectively

$TPCDG$, $TPCNDG$, $TPCSER$ denote private consumption of durable goods, nondurable goods and services, respectively

c_i are constants

In any case, the fuel demand for freight transportation (domestic) and the motor fuel demand for international and military transportation, the steel production and the feedstock consumption by the petrochemical industries, and the labor force share of the service sector are derived in MEDEE-2 by the following econometric equations.

$$TKFRT = c_1 + c_2 \cdot (YAG + YMIN + YMAN + YEN) \quad (A12)$$
$$MISMF = c_1 + c_2 \cdot Y \quad (A13)$$
$$PST = c_1 + c_2 \cdot VAIG \quad (A14)$$
$$FEED = c_1 + c_2 \cdot VAIG \quad (A15)$$
$$PLSER = (PYSER)^{c_1} \quad (A16)$$

where

TKFRT denotes total demand for domestic freight transportation (10^9 ton-km)

MISMF denotes motor fuel consumption for international and military transportation (10^{12} kcal)

PST denotes total steel production (10^6 tons)

FEED denotes total feedstock consumption (10^6 tons)

PYSER denotes the GDP share of the service sector (fraction)

PLSER denotes the manpower share of the service sector (fraction)

ENERGY DEMAND CALCULATIONS

Transportation

Three types of transportation are distinguished in MEDEE-2, namely, passenger, freight, and international and military transportation. Passenger transportation is broken down into an urban and an intercity category. For international and military transportation, only liquid fuels are considered feasible. The motor fuel demand for this type of transportation is treated as a function of GDP.

The fuel demand for domestic freight transportation (measured in net ton-kilometer) is calculated as a function of the GDP contribution by the agricultural, mining, manufacturing, and energy sectors. The modal split, i.e., the allocation to the various modes (rail, truck, inland waterways or coastal shipping, pipeline) must be specified exogenously, as well as the energy intensity (per ton-kilometer) of each mode. Except for rail, where electricity and coal can also be used as an energy source, only liquid fuels are assumed to be used.

Passenger transportation is treated in more detail, because in most countries it accounts for a major share of energy consumption. Total demand for intercity passenger transportation (measured in passenger-kilometers) is calculated from data on population and average distance traveled per person per year. Automobile travel is calculated from data on population, automobile ownership, average distance traveled per car per year, and an average load factor (passenger-kilometer per vehicle-kilometer). The remainder is allocated to public transportation modes (rail, bus, airplane) according to exogenously specified shares. The corresponding vehicle-kilometers are calculated from average load factors for each mode. The energy intensities (per vehicle-kilometer) also have to be specified. As for transportation, only liquid fuels are assumed to be used, except for railways.

The demand for urban transportation is related to the population in large cities (e.g., those with more than 50,000 inhabitants) where mass transportation is feasible. From data on the average distance traveled per day per person in urban areas and on the total population in these areas, the demand for transportation is calculated and allocated to two modes: private automobiles and mass transportation systems. Using average load factors, the passenger-kilometers are converted to vehicle-kilometers. Liquid fuels or electricity can be used as energy sources. The allocation has to be specified by separate parameters, as well as the energy intensity for each mode (per vehicle-kilometer).

All energy demand calculations for the transport sector are made only in terms of final energy.

Industry

Under this label in MEDEE-2, all economic activities except those of the service sector are included. Specifically, these are agriculture, construction, mining, three (or four) manufacturing subsectors, and energy (electricity/gas/water). The energy consumption of the energy sector (and of other energy-related activities, if they can be isolated) is neglected because the energy consumption of conversion activities is calculated at a later stage by the MESSAGE model.

Three types of end-use categories are considered: specific uses of electricity (for lighting, motive power, electrolysis, etc.); thermal uses (space and water heating, low and high temperature steam generation, furnace operation); and motor fuel use (mainly for motive power in nonstationary uses, e.g., in agriculture, construction, and mining).

Because it is in most cases impossible to obtain energy balances in sufficient detail, all present uses of electricity in industry are considered "specific" (in the sense that substitution by other energy sources is unlikely), and all fossil fuels, except motor fuel, are assumed to be consumed for thermal uses. This implies that electricity penetration into thermal uses must be interpreted as incremental penetration above the levels reached today.

Required for the energy demand calculations are the activity level (value added) and the energy intensities (per unit value added) for each sector. The energy intensities must be specified in terms of final energy for motor fuel and electricity and in terms of "electricity equivalent" for thermal uses. The breakdown of thermal uses (space/water heating, low/high temperature steam generation, furnace operation) is assumed to be constant. If the breakdown is not known for each subsector, an average split must be specified.

The change in energy intensities should reflect a change in the specific energy demand per unit of output due to changes of the product mix or due to process integration and other operational improvements.

For thermal uses, the penetration of electricity, district heat, cogeneration, heat pump, and soft solar technologies must be estimated. The remaining energy demand is assumed to be met by fossil fuels and is converted to final energy demand using exogenously specified end-use efficiencies for heating systems, boilers, and furnaces (these must be given relative to electricity). Electricity can penetrate into virtually all thermal uses; the potential market of the other alternatives is restricted to steam and low-temperature uses.

The demand for coke and for petrochemical feedstocks is calculated separately, since they account for a major share of total industrial energy consumption. Coke demand is related to pig iron production, which in turn is related to steel production, and petrochemical feedstock demand is directly related to the value added of basic materials industries, which include petrochemical industries.

Household/Service Sectors

It is well known that in the presently developed countries space heating accounts for the major share of energy consumption in this sector and that with improved insulation this energy demand could be reduced considerably. Especially buildings constructed after the world's awakening to the energy crisis in 1973 have or will have better insulation. To capture this difference, pre-1975 and post-1975 buildings are treated separately. In addition, three types of dwellings are considered: single housing units with central heating, apartments with central heating, and dwellings with room heating only. This is done in order to capture the large difference in the average heat loss of these dwelling types.

The change in the housing stock of the residential sector is determined from data on average family size and population, on demolition of existing dwellings by type, and on construction of new dwellings by type. Allowance is made for reduction of heat loss in old dwellings through retrofitting; the heat loss of post-1975 dwellings is calculated from the average size and the specific heat loss per square meter for each type of dwelling.

Energy demand for water heating, cooking, air conditioning, and the electricity consumption of appliances (such as washing machine, refrigerator, freezer, dishwasher, clothes dryer, vacuum cleaner) is calculated from exogenously specified ownership fractions and/or average annual consumption rates.

The change in the building stock of the service sector is calculated from data on the average floor area per worker and labor force and on the demolition of existing floor area. Allowance is made for improving the insulation of old buildings. Besides thermal uses (space/water heating), two other end-use categories are distinguished, namely, air conditioning and specific electricity uses, for which penetration and/or average consumption rates must be given.

The energy demand calculations for this sector are generally made in terms of "electricity equivalent." For air conditioning, electricity is considered the only energy source; this is also true for heat pumps. In all other instances, the penetration of alternative sources such as electricity, district heating, heat pumps, or soft solar technology must be estimated; the remaining energy demand is assumed to be met by fossil fuels and converted to final energy demand using exogenously specified end-use efficiencies. The potential market for district heat is restricted to large cities, and the potential market for solar is restricted to post-1975 single housing units in the case of space heating; penetration of solar technology for thermal uses in the service sector is assumed to be feasible only in low-rise buildings. A full description of MEDEE-2 is given in Lapillone (1978).

APPENDIX B: THE MESSAGE MODEL

LEO SCHRATTENHOLZER AND MALCOLM AGNEW

MESSAGE stands for *M*odel for *E*nergy *S*upply *S*ystems *A*lternatives and Their *G*eneral *E*nvironmental Impact. It was built by A. Voss, M. Agnew, and L. Schrattenholzer, and represents a significant extension of a model by Häfele and Manne (1974), which focused on strategies for a transition from fossil to nuclear fuels. A comprehensive description of the MESSAGE model – its logic, mathematics, and scope – is given in Agnew *et al.* (1979).

The fundamental features of the model are summarized in Figure B1. A number of primary energy sources and their associated conversion technologies are considered. These include resources and technologies that could permit an essentially unlimited supply of energy – the fundamental point of the whole exercise being to explore possible transitions to energy systems states based on more or less unlimited resources such as ^{232}Th, ^{238}U, and solar energy.

Each primary energy source (except solar and hydroelectric power) is subdivided into an optional number of classes, taking account of price of extraction, quality of resources, and location of deposit. These primary sources are then converted directly (e.g., by crude oil refining) or indirectly (e.g., electrolytic hydrogen) into secondary energy. Secondary energy is exogenous to MESSAGE and is provided by the MEDEE-2 model as time series data for electricity, soft solar, district heat, and solid, liquid, and gaseous fuels.

The MESSAGE model is a dynamic linear programming (LP) model, i.e., the planning horizon is divided into n time periods of equal length. The variables of the model are expressed in period-averages of annual quantities.

The objective function is the sum of discounted costs for fuels (primary energy), operating/maintenance costs, and capital costs for providing the energy demand over the planning horizon (1975–2030).

The equations of the models are roughly as follows (indices are sometimes omitted if it seems to facilitate understanding):

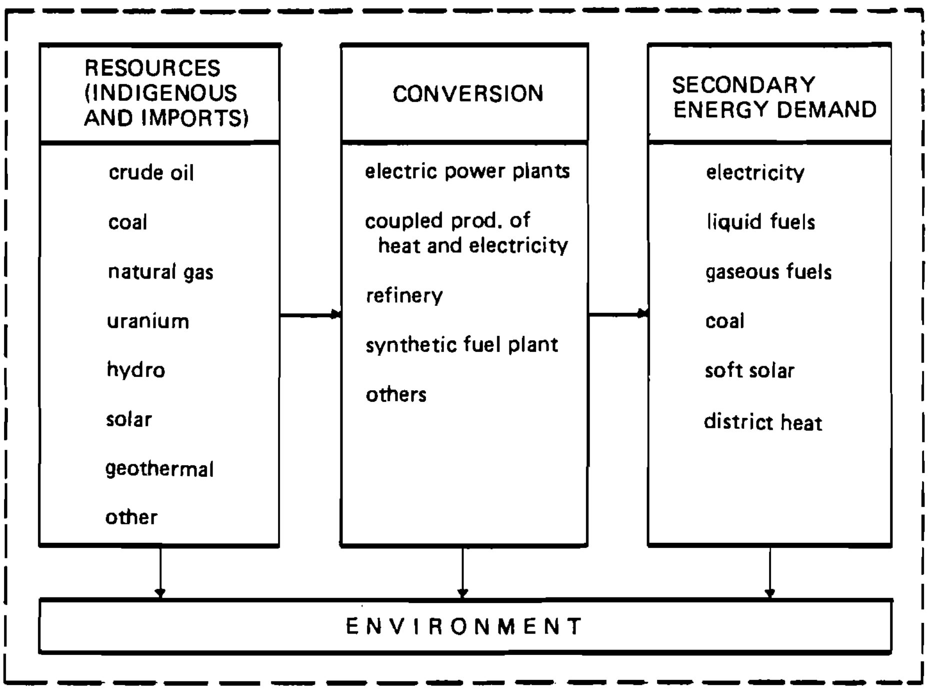


FIGURE B1 Schematic description of MESSAGE.

Objective Function

The objective function of the MESSAGE model is the sum of discounted costs of capital, operating-maintenance, and fuels (primary energy):

$$\sum_{t=1}^{n} \beta(t)\, 5 \left\{ b^T r(t) + c^T x(t) + d^T y(t) \right\} \tag{B1}$$

where

t is current index of time period
n is number of time periods
$\beta(t)$ is discount factor
5 is number of years per period
b is vector of energy resources costs
r is vector of resource activities (LP variables)
c is vector of operating/maintenance costs
x is vector of energy conversion activities (LP variables)
d is vector of capital (investment) costs
y is vector of capacity increments (LP variables)

Resource Constraints

The following resource constraint is defined for each resource and for each category:

$$\sum_{t=1}^{n} 5r(t) \leqslant Av \tag{B2}$$

where

$r(t)$ is annual extraction in period t
Av is availability of resource

Resource Requirement

This equation is specified for each time period and for each resource:

$$\sum_{j=1}^{J} r_j(t) \geqslant \sum_{l} (v_l x_l(t) + w_l y_l(t) - w_l y_l(t-6)) \tag{B3}$$

where

j is index of resource category
J is number of resource categories
v_l is specific consumption by production activity x_l
w_l is inventory requirement for capacity increment y_l

Capacity Equations

The following equation is specified for each time period, for each technology, and for each load region that is supplied by this technology.

$$x_j \leqslant Cap \cdot h_j \cdot pf \text{ (where } Cap(t) = \sum_{\tau=t-5}^{t} 5y(\tau)) \tag{B4}$$

where

j is index of load region
Cap is capacity
h_j is load duration of load region j
pf is plant factor

Demand Constraints

The following equation is specified for each time period, for each demand sector, and for each load region.

$$\sum_{i} \eta_{ij} X_i \geqslant DM_j \tag{B5}$$

where

j is index of demand sector

n_{ij} is conversion efficiency (or equal to 0 if x_i does not supply demand sector j)
DM_j is annual demand for secondary energy in sector j

Build-up Constraints

The following equation is specified for some (primarily new) technologies and for each time period.

$$y(t) \leqslant \gamma y(t-1) + g \tag{B6}$$

where

γ is growth parameter
g is constant, allowing for start-up

Emission Constraints

The following equation is specified for each type of pollutant and for each time period.

$$b = \sum_i em_i x_i \tag{B7}$$

where

b is total emissions (LP variables)
em_i is specific emissions of technology i

Pollutant Concentration Constraints

The following is a non-binding constraint, which is defined for each time period and for those pollutants whose concentrations are to be calculated (e.g., Krypton, Carbon dioxide).

$$\sum_{\tau=1}^{t} 2^{5(\tau-t)/t2b} \tag{B8}$$

where

τ, t are indices of time periods
5 is the number of years per time period
$t2$ is the half life of pollutant

APPENDIX C: THE IMPACT MODEL

YURI KONONOV

Once an optimal energy strategy is identified, it is necessary to understand the requirements for corresponding direct and indirect energy investments. The first version of the IMPACT model was built at the Siberian Power Institute by Yuri Kononov and Victor Tkchachenko. At IIASA the model was developed further by Yuri Kononov, with the help of Todor Balabanov. It has been adjusted for identifying and comparing long-range regional strategies for the transition to new energy sources.

MODELING TECHNIQUES

IMPACT belongs to the set of energy-oriented dynamic input–output models, explicitly accounting for lags between the start of investment and the putting into operation of production capacities. It consists of linear and nonlinear equations that describe the following for each year of the period concerned: balance of production of individual products and services and their consumption in operating and building the energy systems and related branches; the conditions for introducing extra capacities in energy-related branches; and investment and WELMM requirements.

MODEL CAPABILITY

For each given energy strategy, the model determines:

- Investment in energy system development;
- The required putting into operation of capacities in energy-related branches of industry and corresponding (indirect) capital investment;
- The required output of different types of materials, equipment, and services to provide operational and construction requirements of the energy system and related branches; and
- Direct and indirect WELMM requirements.

All these indicators are evaluated for each year of the period considered.

The model describes the building up of production capacities as a direct part of the energy supply system and its related branches. In this way lead times of construction and related consumption of equipment and material are taken into account. This is done by identifying input–output relations between sectors of the economy important for the energy supply systems:

iron ore mining
primary iron and steel manufacturing
fabricated metal products
nonferrous metal ore mining
nonferrous metals manufacturing
chemical products
plastic and synthetic materials
petroleum products
stone, clay, and glass products
lumber and wood products
miscellaneous materials
engines and turbines
electrical equipment
mining equipment
oil field equipment
construction equipment and machineries
material handling equipment
metalworking equipment
instrument and control equipment
transportation equipment
special industry equipment
general industry equipment
fabricated plate products
miscellaneous equipment
export goods I
export goods II
construction in energy sectors
construction (nonenergy)
transport (nonenergy)
maintenance and repair construction

THE EQUATION SYSTEM OF IMPACT*

The direct requirements of the energy supply system for products of energy-related sectors are expressed as

*Matrix notation is used throughout the section. The letters t or τ in parentheses denote vector-valued time functions. A bar denotes an exogenously given input.

$$Y(t) = A_1 \bar{X}_e(t) + \sum_{\tau=1}^{t+\hat{\tau}} F_1^{(\tau-t)} \bar{Z}_e(\tau) \tag{C1}$$

where

$Y(t)$ is the vector of direct investment and operational requirements of the energy supply system for products of energy-related sectors in the year t

$\bar{X}_e(t)$ is the vector of annual energy production in the year t

$\bar{Z}_e(t)$ is the vector of required additional capacities of the energy supply system in the year t

A_1 is the matrix of contribution coefficients of energy-related sectors to the construction and operation of energy production per unit of activity

$F_1^{(\tau-t)}$ is the matrix of contribution coefficients of energy-related sectors in the year t to putting into operation the additional capacities of the energy supply system in the year t ($t \leqslant \tau \leqslant t + \hat{\tau}$)

Total (direct and indirect) material and equipment requirements of the energy supply system are expressed as

$$X_1(t) = A_2 X_1(t) + A_3 X_2^{\text{in}}(t) + Y(t) \tag{C2}$$

where

A_2 is the matrix of input–output coefficients

A_3 is the matrix of materials and equipment requirements coefficients per unit of investment in energy-related sectors

$X_1(t)$ is the vector of output in energy-related sectors

$X_2^{\text{in}}(t)$ is the vector of indirect capital investments in energy-related sectors

Direct capital investment in the energy supply system is expressed as

$$X_2^{\text{d}}(t) = \sum_{\tau=t}^{t+\hat{\tau}} F_2^{(\tau-t)} \bar{Z}_e(\tau) \tag{C3}$$

Indirect capital investment in the energy supply system is expressed as

$$X_2^{\text{in}}(t) = \sum_{\tau=t}^{t+\hat{\tau}} F_3^{(\tau-t)} Z_1(\tau) \tag{C4}$$

Total (direct and indirect) capital investment in the energy supply system is expressed as

$$X_2^{(t)} = X_2^d(t) + X_2^{\text{in}}(t) \tag{C5}$$

where

$F_2^{(\tau-t)}, F_3^{(\tau-t)}$ are, respectively, the matrices of capital investment coefficients in the year t to put into operation the additional capacities of the energy supply system and energy-related sectors in the year t

$Z_1(t)$ is the vector of new additional capacities in the energy-related sectors in the year t

$X_2^d(t)$ is the vector of direct capital invesment in the energy supply system

Vector $Z_1(t)$, with vector components $Z_1^{(1)}, \ldots, Z_1^{(k)}$, must satisfy the following conditions:*

$$Z_1^{(i)}(t) = \begin{cases} \min\limits_{\tau \leqslant t} [X_1^{(i)}(t+1) - X_1^{(i)}(\tau)] & \text{if this value is positive} \\ 0 & \text{otherwise} \end{cases}$$

for every $i \in \{1, 2, \ldots, k\}$

Vector notation is used in the model for simplicity reasons. This equation is therefore written as

$$Z_1(t) = \max\left[\min_{\tau \leqslant 1} \left(X_1(t+1) - X_1(\tau)\right): 0\right] \qquad \text{(C6)}$$

The model also includes an equation for calculating the direct and the indirect expenses of the WELMM resources. This equation is written as

$$X_3(t) = A_4 \bar{X}_e(t) + A_5 X_1(t) + A_6 X_2^{\text{in}}(t) + \sum_{\tau=t}^{t+\hat{\tau}} F_4^{(\tau-t)} \bar{Z}_e(\tau) \qquad \text{(C7)}$$

where

$X_3(t)$ is the WELMM expenditures in the year t
A_4 is the matrix of direct operational WELMM coefficients
A_5 is the matrix of indirect operational WELMM coefficients of energy-related sectors
A_6 is the matrix of indirect constructional WELMM coefficients of energy-related sectors
$F_4^{(\tau-t)}$ is the matrix of direct constructional WELMM coefficients in the year t to put into operation new energy capacities in the year t

Equations for evaluating air and water pollutant emissions of the energy supply system and the energy-related sectors can be written analogically.

The drivers for IMPACT's relations are $\bar{X}_e(t)$ and $\bar{Z}_e(t)$; these exogenous variables can be obtained from an energy supply model (e.g., the IIASA MESSAGE model).

An algorithm has been developed for solving equations iteratively. This algorithm, as well as other details of IMPACT's structure, logic, and scope are described in Kononov and Por (1979).

*In order to take into account *installed* capacity requirements, this expression can be replaced by

$$Z_1^{(i)}(t) = \begin{cases} \min\limits_{\tau \leqslant t} \left[X_1^{(i)}(t+1) - \dfrac{X_1^{(i)}(\tau)}{(1-p)^{t-\tau+1}}\right] & \text{if this value is positive} \\ 0 & \text{otherwise} \end{cases}$$

for every $i \in \{1, 2, \ldots, k\}$ where p is the rate of replacement.

APPENDIX D: THE MACROECONOMIC MODEL

HANS-HOLGER ROGNER

The conceptual first step in the Energy Systems Program's modeling loop is a single sector, structural model of a macro economy developed by Hans-Holger Rogner at IIASA. The fundamental logic of MACRO is described below.

A certain population is input exogenously to the model; the population model of N. Keyfitz (Keyfitz 1979) is used here. In the MACRO model the labor force is determined by the population adjusted for the retired population and the level of the real wage rate. The estimated parameters show a reduction in labor force with a growing population and a positive change with respect to the real wage rate.

$$LABOR = 113.25 \frac{w\text{-}RATE}{p} - 0.898(Pop - Pop\ 65) + 98.175 \qquad \text{(D1)}$$

The average number of hours worked per week is derived as follows

$$HOURS = (-0.133\ PROP\text{-}UN - 0.166\ TIME + 41.2)\xi \qquad \text{(D2)}$$

PROP-UN is the percentage of the labor force that is unemployed. *TIME* is in years. ξ is the first of three fundamental adjustment parameters that allow for defining alternative scenarios. It describes the discrepancy between normative requirements and expected trends derived from time series data of the sampling period. $\xi = 1$ means that observed trends prevail.

Equations (D1) and (D2) together provide the calculation of total potential annual man-hours available to an economy.

The following relations were derived from time series data for the USA over the period 1947–1977. (They are now established for other regional applications of the model.)

Equations (D3a and b) have been estimated over that sample period 1947–1977. For that period, actual man-hours worked have been derived from gross national product (GNP) and the relative prices of capital and labor assuming that production is based on cost minimization behavior of producers.

$$MANHOURS = 0.042 GNP\$72 + 0.068 GNP\$72 \left(\frac{COST\text{-}k}{w\text{-}RATE}\right)^{1/2} - 1.04 TIME + 59.9 \quad \text{(D3a)}$$

GNP\$72 is the GNP in 1972 US dollars, *COST-k* is the cost of capital; and *w-RATE* is the wage rate. The time term (− 1.04*TIME*) describes an increase of labor efficiency that may or may not be continued in long-range forecasts.

As a ceiling, equation (D3b) specifies the planning horizon for full employment.

$$MANHOURS = HOURS \frac{EMPLOY - 21.69}{36.33} \quad \text{(D3b)}$$

A second fundamental relation describes desired capital stock; desired in the sense that capital cannot adjust to the level desired within one time period.

$$K^*\$72 = \left[\sum_{i=0}^{7} w_i GNP\$72_{-i} + \sum_{i=0}^{4} v_i GNP\$72_{-i} \left(\frac{w\text{-}RATE_{-i}}{COST\text{-}k_{-i}}\right)^{1/2} + \text{constant}\right] \eta \quad \text{(D4)}$$

w_i and v_i are weights for the time lags in the reaction of the desired capital stock to past growth of GNP. η can describe the increase of the capital–output ratio (exogenously imposed) that could become necessary when capital-intensive energy technologies are to be introduced.

The investments I are determined by using the desired capital stock K^*, the previous period's capital stock, and depreciation.

$$I\$72 = 0.85(K^*\$72 - K\$72_{-1}) + DEP\$72 + 7.6 \quad \text{(D5)}$$

Consumption C is a lagged function of spendable income YS taking into account that the full reaction of consumers to changes in spendable income does not occur immediately and that the consumption level of the present period is also related to past levels of spendable income.

$$C\$72 = \sum_{i=0}^{3} u_{-i} YS\$72_{-i} - \text{constant} \quad \text{(D6)}$$

u_{-i} are weights. YS corresponds to the following relation

$$YS\$72 = GNP\$72 - DEP\$72 - (TAXIN\$72 + TAXES/p)\zeta + (GT + BT + IS)/p \quad \text{(D7)}$$

DEP\$72 is depreciation of capital stock; *TAXIN* and *TAXES* are indirect and direct taxes, respectively; *GT* are government transfers such as welfare; *BT* are business transfers; *IS* is the spendable income interest; and p is the deflator. ζ is the third of the three fundamental adjustment parameters relating norms to trends.

The various components must satisfy the fundamental identity

$$GNP = C\$72 + I\$72 + G\$72 + EX\$72 \qquad \text{(D8)}$$

G are government expenditures for goods and services and EX is net export (balance).

The GNP is calculated by applying a Cobb-Douglas Function with constant return to scale.

$$GNP\$72 = 0.6238 K\$73^{0.3528} MANH^{0.6472} \exp(0.007\, TIME) \qquad \text{(D9)}$$

These equations present the core of the model's logic. Yet they are not an exhaustive set; the full MACRO model will be described in a later report.

As well as annual fluctuations, MACRO describes the evolution of the US economy between 1947 and 1975 ($\xi = \eta = \zeta = 1$) with an accuracy of a few percent. It is simple and transparent enough that one may make runs to the year 2030 and thereby evaluate the interplay among the various parameters. The numerical coefficients presented here are, of course, the results of a regression analysis and refer to a special case in space (USA) and time (1947–1977). Variation of the values of the parameters ξ, η, and ζ is a first step toward improving normative scenarios. Another way to improve the normative scenarios is to change the various numerical coefficients; however, the results are less easy to interpret.

APPENDIX E: THE GAMING MODEL

ALEXANDER PAPIN

Developed at the Siberian Power Institute under the direction of Professor Alexej Makarov, the Gaming Model (GM) was designed to allow an aggregate assessment of the long-term tendencies in world oil trade. It is available at IIASA. By means of sophisticated data on liquid fuel demand and oil production by groups of countries (regions) over time, the model yields estimations of oil price dynamics and quantities of internationally traded oil.

The approach to world oil market modeling assumes that economic factors are primary factors in affecting conditions of long-term world energy development; social and political factors are treated as more temporary. Thus, economic factors were chosen as the subject for modeling, while political and social factors can be introduced as exogenous controls.

In the GM, the process of trading in the world oil market is simulated as a game (developing in time) of some partners or groups of countries (regions). Each region is characterized by specific conditions of energy development, in particular, economic values of oil imports/exports; and objectives (interests) as a participant in the world oil trading. These characteristics, when incorporated, form regional submodels within the GM that allow the multiple optimization of regional oil supply systems during the process of simulation.

Regional results are coordinated with the special "compromise-searching" procedures of the GM. These are based on three different assumptions about the world oil market:

- Equilibrium (ideal competition among exporters and importers);
- Dominance of exporters with full unity among members of their coalition (monopoly); and
- Dominance of exporters with competition among members of their coalition (cartel).

In its dialogue regime, GM allows variations in critical regional and inter-regional oil trade factors, for example, regional oil demand and supply elasticities, potentials and costs of regional oil production, exporters' and/or importers' oil trade quotas, and composition of coalitions of oil traders. In this way, one can simulate a broad spectrum of evolutionary paths for the world oil market.

ACKNOWLEDGMENTS – THE ENERGY MODELING TEAM

Energy modeling at IIASA is a team effort, in every sense. This report summarizes the integrated character and result of the work of that team, an international group of individuals. From the outset, the effort has been led by Professor Wolf Häfele, Leader of the Energy Systems Program at the International Institute for Applied Systems Analysis (IIASA). The conception and eventual design of the modeling loop owes much, if not all, to his guidance.

The contributors to the model set can perhaps best be acknowledged by listing the models in use:

MACRO: This model was developed at IIASA by Morris Norman and Hans-Holger Rogner.

MEDEE-2: The MEDEE approach was developed at the University of Grenoble. It was brought to IIASA and adopted for our analyses by Bruno Lapillonne, with Morton Müller. The model is currently being operated by Alois Hölzl and A. Khan.

MESSAGE: Starting with the Häfele–Manne model and following the extension by Atsuyki Suzuki, Alfred Voss, Leo Schrattenholzer, and Malcolm Agnew revised and operated this main tool of the modeling loop. Leo Schrattenholzer and John Eddington currently operate the model.

IMPACT: Developed at the Siberian Power Institute by Yuri Kononov and Victor Tkchachenko, the IMPACT model was brought to IIASA, adapted for use, and operated by Yuri Kononov. Todor Balabanov assisted in the adaptation and operation of the model.

OIL TRADE: Based on a gaming model developed by Alexej Makarov at the Siberian Power Institute. Alexander Papin has calculated oil trade patterns for the scenarios; he is currently in the process of adapting the Makarov gaming model for use at IIASA.

INTERLINK and ENERDYM: Igor Zimin extended an input–output model, INTERLINK, of a national economy for potential use within the

modeling loop. He also developed a resources model, ENERDYM, capable of assessing the maximum potential production rates for various fossil fuels, given basic geological data. Both of these models are in the process of being integrated into the modeling loop.

In addition, other models and modelers have contributed to the concepts and insights behind the scheme described in this report. Jyoti Parikh adapted a simulation model of India, SIMA, for some case study analyses. She also developed a cross-country regression model called SIMCRED that was useful in first attempts at gaging energy use in developing regions. Jean-Michel Beaujean, with Tomas Müller, developed a simplified energy demand model, MUSE, that helped in our early probings with that complex subject. William Orchard-Hays led the systems programming and computational efforts for several of the models.

All of these individuals, and more, have contributed greatly to the major energy modeling effort broadly described and illustrated in this report. The modelers not only run the models but also provide expert judgments on input parameters and share in evaluating results.

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