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Häfele, W., Manne, A.S. and Charpentier, J.P.

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PROCEEDINGS
OF
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ON
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Schloss Laxenburg
2361 Laxenburg
Austria

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The Institute assumes full responsibility for minor editorial changes made in grammar, syntax, or wording, and trusts that these modifications have not abused the sense of the writers' ideas.

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List of Participants

Chairman of Conference: Prof. Wolf Häfele, Energy Project Leader

Co-Chairman: Prof. Alan S. Manne

Scientific Secretary: Dr. Jean-Pierre Charpentier

AUSTRIA

Dr. Peter Sint
Institut fuer Sozio-oekonomische
Entwichklungsforschung
Fleischmarkt 22
1010 Wien

Dr. Hans Aubauer
2. Physikal. Institut
der Universität Wien
Strudelhofgasse 4
1090 Wien

BULGARIA

Eng. Vanio Mitov
c/o The National Center for
Cybernetics and Computer
Techniques
8, Slavjanska Street
Sofia

CANADA

Dr. Paul G. Bradley
Department of Economics
University of British Columbia
2075 Westbrook Place
Vancouver, British Columbia

Dr. F.W. Gorbet
Associate Senior Economic
Advisor
Department of Energy,
Mines and Resources
Ottawa, Ontario K1A OE4

Dr. I.A. Stewart
Senior Economic Advisor
Department of Energy,
Mines and Resources
Ottawa, Ontario K1A OE4

CZECHOSLOVAKIA

Ing. Milos Drahny, Csc.
Stellvertreter des Direktors des
Forschungsinstitutes fuer
Energetik, Power Institute
Partyzanska 7a
Praha 7

Ing. Imprich Lencz, Csc.
Power Institute
Partyzanska 7a
Praha 7

FEDERAL REPUBLIC OF GERMANY

Dipl. Ing. Gerd Modemann
Techn. Hochschule Aachen
Institut fuer Elektrische Anlagen
und Energiewirtschaft
Lehrauftrag Leistungsreaktoren
Aachen

Dr. Richard Denton
Institut fuer Systemtechnik und
Innovationsforschung der
Fraunhofer-Gesellschaft e.V.
Breslauer Strasse 48
75 Karlsruhe

Mr. Paul Winzke
Techn. Hochschule Aachen
Institut fuer Elektrische Anlagen
und Energiewirtschaft
Lehrauftrag Leistungsreaktoren
Aachen

FRANCE

M. Robert Janin
Chef du Service des Etudes
Economiques Générales
Electricité de France
2, rue Louis Murat
75008 Paris

M.D. Blain
Chargé de Mission
Ministère des Economies et
des Finances
Direction de la Prévision
9, rue Croix des Petits Champs
75001 Paris

M. Levi
Service des Etudes
Economiques Générales
Electricité de France
2, rue Louis Murat
75008 Paris

ITALY

Dr. L. Biondi
Montedison Company
Largo Donegani 2
Milan

JAPAN

Dr. Mitsuo Takei
Manager
Research Division
The Institute of Energy
Economics
No. 10 Mora Bldg.
28 Nishikubo Sakuragawa-Cho
Minato-Ku
Tokyo

Dr. Fusao Mori
Chief Engineer
Central Research Laboratory
Mitsubishi Electro Corporation
2-3 Morunouchi
2-Chome Chiyoda-Ku
Tokyo

Mr. Yukio Sekiya
The Institute of Energy
Economics
No. 10 Mori Bldg.
28 Nishikubo Sakuragawa-Cho
Minato-Ku
Tokyo

POLAND

Prof. Jerzy Holubiec
The Polish Academy of Sciences
c/o Academia Palazza
delle Scienze
2 Vicolo Doria
00187 Rome

Prof. W. Frankowski
Instytut Badan Jadrowych
Swierk k/Warszawy
Warsaw

UNITED KINGDOM

Prof. P.J. Deam
Energy Research Unit
Queen Mary College
Mile End Road
London E1 4NS

U.S.A.

Dr. Kenneth C. Hoffman
Head Engineering Division
Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

Mr. Frank J. Alessio
Manager
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, California 94304

Prof. Thomas Connolly
Department of Mechanical
Engineering
Stanford University
Stanford, California 94305

Mr. Gordon Hough
Arbesbachgasse 4/4/15
1190 Wien

Prof. Gordon Kaufman
Sloan School of Management
Massachusetts Institute of
Technology
Cambridge, Massachusetts 02139

Prof. Dale W. Jorgenson
Department of Economics
Harvard University
Cambridge, Massachusetts 02138

U.S.A. (con't)

Mr. E. Schmidt
Assistant to Vice President
for Research and Development
General Electric Corporation
570 Lexington Avenue
New York, New York

Dr. Ernest G. Silver
Institute for Energy Analysis
P.O. Box 117
Oak Ridge, Tennessee 37830

Mr. James A. Walker
Management Associate
Executive Office of the
President
New Executive Office Bldg.
Room 8104
Washington, D.C. 20503

U.S.S.R.

Acad. Styrikovich
The Academy of Sciences
State Committee for USSR
Council of Ministers for Science
and Technology
11, Gorky Street
Moscow

Dr. Minaev
The Academy of Sciences
State Committee for USSR
Council of Ministers for Science
and Technology
11, Gorky Street
Moscow

Dr. Kichatov
The Academy of Sciences
State Committee for USSR
Council of Ministers for Science
and Technology
11, Gorky Street
Moscow

Dr. Kuzovkin
The Academy of Sciences
State Committee for USSR
Council of Ministers for Science
and Technology
11, Gorky Street
Moscow

Representatives from International Organizations

IAEA (Kärntner Ring 11, 1010 Wien)

Mr. Rurik Krymm
Head of Economic Study Section
Division of Nuclear Power Reactors

Dr. Georg Woite
Division of Nuclear Power and Reactors

OPEC (Dr. Karl Lueger-Ring 10, 1010 Wien)

Dr. A. Khene
Secretary General OPEC

Mr. M. Olorunfem
Senior Financial Analyst

Mr. C. Faidi
Senior Exploration Officer

UNITED NATIONS

Mr. Clement Lopez-Polo
United Nations Economic
Commission for Europe
Palais des Nations
1211 Geneva 10

IIASA Staff

Professor Howard Raiffa	Director
Dr. Andrei Bykov	Secretary to IIASA

RESEARCH SCHOLARS

Prof. Wolf Häfele	(Project Leader)	Energy Systems (Chairman)
Dr. Rudolf Avenhaus		Energy Systems
Dr. Jean-Pierre Charpentier		Energy Systems (Scientific Secretary)
Prof. Michel Grenon		Energy Systems
Dr. Nikolai Kourochkin		Energy Systems
Prof. Alan S. Manne		Energy Systems (Co-Chairman)
Dr. Cesare Marchetti		Energy Systems
Dr. Richard Patzak		Energy Systems
Dr. Atsuyuki Suzuki		Energy Systems
Dr. Norbert Weyss		Energy Systems
Mrs. Truus Koopmans		Energy Systems
Dr. Alfred Voss		Energy Systems*
Dr. Dieter Sellingschegg		Energy Systems*
Dr. Robert Treitel		Energy Systems*
Dr. Jacques Girod		Energy Systems*
Prof. George Dantzig	(Project Leader)	Methodology
Prof. Tjalling Koopmans		Methodology
Dr. Johann Millendorfer		Methodology

SCIENTIFIC RAPPORTEURS

Dr. Dieter Sellingschegg	Working Group I
Dr. Jean-Pierre Charpentier	Working Group II
Dr. Norbert Weyss	Working Group III
Dr. Jean-Pierre Ponssard	Working Group IV

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*Short-term appointment.

Agenda

Tuesday, May 28

Morning

8:30- 9:15		REGISTRATION	
		SESSION 1	
9:15- 9:30		Welcome and Introduction	(H. Raiffa, W. Häfele)
9:30-10:15	(A)	Electricity and Energy Systems	(R. Janin - France)
10:15-11:00	(B)	A Comparison of Mathematical Models for Long-Term Planning of the Economic Operating and Extension of a System of Power Stations	(G. Modemann - FRG)
11:00-11:15		Coffee Break	
11:15-12:00	(C)	A Study of Infrastructural Impact of Long Range Energy Transports	(Acad. Styrikovich - USSR)
12:00-12:45	(D)	Strategies for a Transition from Fossil to Nuclear Fuels	(W. Häfele, A. Manne - IIASA)
12:45-14:30		Lunch	

Afternoon

14:30-17:30	Discussions in Working Groups

Wednesday, May 29

Morning

SESSION 2

9:30-10:15	(A)	World Energy Supply Analysis	(R. Deam - UK)
10:15-11:00	(B)	Interfuel Subsitution and Technological Change	(K. Hoffman - USA)
11:00-11:15		Coffee Break	
11:15-12:00	(C)	A Concept for Evaluation of Timing of Transition into a Non-Fossil Energy Economy	(M. Takei - Japan)
12:00-12:45	(D)	Progress Report on a Review of Energy Models Developed in Various Countries	(J.P. Charpentier - IIASA)
12:45-14:15		Lunch	

Afternoon

14:15-16:00	Special Reports	
	New Ways and New Possibilities of Modelling the Electric Power System Development	(I. Lencz - CSSR)
	Energy Policy Project of the Ford Foundation	(D. Jorgenson - USA)
	GLOSAS Proposal	(G. Hough - USA)
16:00-16:15	Coffee Break	
16:15-18:00	Informal Discussion, including Reports from the Working Groups and further Research Topics	

Introductory Remarks by the Institute Director

H. Raiffa

The research program at IIASA started up in the summer of 1973 with the arrival of our first scientists, and by this summer we should be about 60 strong in the scientific area. The research projects include nine principal areas of research. Three of them are service-oriented: methodology, design and management of large organizations, and computer systems and sciences. Then there are what we call the six "applied" projects: integrated industrial systems, urban and regional systems, ecology, bio-medicine, energy, and water resources. We think of the research program as being conducted in a sort of matrix format, where we have our applied projects from energy all the way to the industrial projects, and then the remaining three projects involving methodology, computer sciences, and organization systems are conceived to be service oriented. In these service-oriented projects we hope to incorporate a wide range of skills by employing applied mathematicians, computer scientists, people in managerial sciences and behavioral sciences, policy analysts and including even lawyers, historians, etc.

If we look at the energy project, there are now about 10 or 12 people that are primarily in the project itself, but that group is enhanced by a group of service-oriented people who work in relationship with the energy project, as well as in the water and ecology areas. Now, some of you might wonder why we chose to have nine projects when we have such a small professional staff here. The choice of a project is a combination of science and politics, and it was very difficult to get agreement on one or two topics. I think by having a menu of interrelated projects we are able to have an acceptable program. But this presents terrible problems for us. What we hope we will do in our research strategy is have a four-pronged attack.

We are busy at this point building up our inhouse research capability and we hope to draw scientists from all our national member organizations. We are now 13 institutions from 13 nations supporting IIASA, but gradually we will expand at the rate of 2 or 3 new national member organizations per year.

The first phase of our program is the building up of our inhouse research activities. The energy project is probably the most advanced in terms of the time-table of our projects. We have an asymmetric rate of development of the various projects. We are hoping that IIASA eventually will become part of a network of research institutions and we hope that we will be able to work in collaboration with other international as well as national institutions. One of the international institutions with which we collaborate in the energy area is obviously the International Atomic Energy Agency (IAEA, located here in Vienna), but in other projects we will be dealing with the UNESCO, WHO, WMO, and other members of the U.N. family. Then there are institutions like IFAC, IFIP and others of similar ilk where we can hope to work out some collaborative effort. But in addition to collaboration with international institutions, we hope that we will have a strong linkage with institutions within nations. Thus, for example, the Institute of Control Science in Moscow is a natural link to us, and many of the things that we will be doing here they will support in terms of their research organization. We hope in the meteorological area, for example, to get cooperation with such institutions as the British Meteorological Office, NCSR in Boulder, Colorado, the Hydrometeorological Institute in the Soviet Union, etc.

We have an obligation not only to do research of our own and in collaboration with others, but to be what we call a sophisticated clearing-house for information--we have an exchange agency role: to find out what is being done in different places that is of relevance to our research program here, and to be catalyst in that kind of dissemination. One way of informing a wider community of the research efforts that are going on, on topics of relevance to our research program here, is to have international conferences and working seminars, of which this is one. I hope that through this means we will not only be able to get an exchange of information, but that maybe some of the activities that are done here in the next two days will be the source of collaborative efforts of our researches here and research institutions elsewhere.

Introductory Remarks by the Energy Project Leader

W. Häfele

When the idea arose to have an energy project here at IIASA, the intention was to accomplish two things simultaneously: first, to make a substantial contribution to the problem of energy as such, and second, within this effort, to develop methods to deal with energy systems, that is to say methods that permit dealing with the system aspect of energy. The methodological requirements for this task are high, and the hope is that in dealing with energy we can learn something of relevance to the methodology of systems analysis.

Against this background the Energy Project is concentrating not so much on a detailed investigation of a specific aspect of energy; neither are we concentrating on the question of how to improve the performance of a transformer, for example, or of a nuclear reactor. There are wide communities, engineering communities and others, in the world that are highly capable of fulfilling these tasks. Our function as we see it is to identify problems such as the question of interface, and others that still have to be identified or that come up if the scale of energy activities becomes wide and eventually global in nature. Thus we have learned that energy production is the major area of interest, but also the handling of energy is of concern, or what we call the embedding of energy into various spheres, such as the atmosphere, the hydrosphere, and the sociosphere. As a consequence we are addressing ourselves to a number of questions that were not necessarily explicitly and extensively studied in the past. For instance, we are trying to identify the effect of waste heat on the climate, we are trying to understand the establishment of standards that are typical of the development of technology, and we are trying to do something about risk evaluation, with the understanding that they are the driving forces of modern technology.

The goal which we hope to achieve eventually is to be of help to the decision maker. That is to say, we have to evaluate and execute methods that allow for the comparison of options. They are options for the provision of long-term energy, for instance, the nuclear option, the solar option, or the geothermal option.

All this then immediately leads to the identification of the timing of the problem: which problem is first, which is second? In what respect can we take a little time and carefully prepare ourselves for a very challenging problem which might face us slightly later in the time ahead? Quite often it has been observed that it is easy to predict certain features of the future. Yet it is by far more difficult to say when they are going to happen. Let me state that I, for myself, had anticipated an energy crisis in the foreseeable future, but at the time I did not understand that it would arrive so soon. For these reasons the identification of the timing of the problem in our judgment is a major goal for systems analysis in the field of energy.

A specific conclusion of an evaluation of timing would be to identify the following strategies: What is to be done on which time scale and in what perspective? To what extent, for instance, is energy conservation possible? What is the phasing of various actions to be taken in the energy field? Here we need some sensor that tells us about possible reactions, for instance, to energy conservation steps, or about the nature of the consequences if the partition between electric and non-electric secondary energy were changed.

We feel that this sensor that helps us to assess the evaluation of timing and strategies is energy modelling. I am very grateful, therefore, for the possibility of being with you today, and I am happy that for two days we have the opportunity of dealing with the problem of mathematical modelling of energy demand and supply. If this is done in a sophisticated manner, these techniques can be used for the identification of necessary steps, for instance, in the R & D field, in investments or with regard to necessary infrastructural improvements. We cannot afford to do it by trial and error. We rather have to do it on the basis of mathematical modelling. The purposes of this conference are two-fold: on the one hand, it will familiarize us with the latest accomplishments in that field, and, on the other hand, it serves as a platform of exchange, or what Prof. Raiffa called "hopefully sophisticated but nevertheless a clearinghouse."

This meeting today has two formal morning sessions, where several papers will be presented as indicated in the agenda. This afternoon there will be discussions in working groups, and, with a sufficient number of historical rooms available, it will be possible to have four parallel sessions that will concentrate on various specific topics as they come up in the discussions. At the end of the morning discussion, perhaps all of us should discuss which topics should be central to the afternoon discussions. Naturally, in organizing a conference, one is well advised to prepare possible suggestions and to emphasize possible subjects for discussions. Let me repeat, however, that these proposed topics can be discussed, if so desired, but we do not necessarily have to stick to them. On Wednesday afternoon we will try to have a conclusion or a discussion of further research topics. This would allow everybody to make statements or observations, if he desires to do so, and this brings me to the end of my introductory remarks.

PAPERS PRESENTED

Electricity and Energy Systems

Daniel Blain, Robert Janin, and P. Bernard

The most characteristic feature of the development of electricity consumption in France during the twenty years 1950-1970 is its regularity. Indeed, during this period, a fairly clearly marked dichotomy could be observed in the power market, in which two separate and distinct sectors were apparent: the fossil energy sector (coal and liquid or gaseous hydrocarbons), on the one hand, and the electricity sector on the other.

There were doubtless some links between these two sectors, owing to the fact that the second had to obtain suplies from the first for producing secondary electric energy, which expanded fairly rapidly due to the fact that hydraulic sites capable of being equipped economically became progressively exhausted. But there were hardly any downstream links in the system, owing to the fact that the structure of final uses for power in the two sectors proved to be remarkably stable. And so, whereas different fossil-type energy sources competed very actively on the heating market particularly, the growth of electricity took place essentially in captive markets, where the use of electricity was practically not contested: lighting, teletransmission systems, electrolysis, metal refining, power for small and medium sized units.

Whereas there were sometimes links between these two sectors (for rail transport, for example), they were not numerous and were insufficient to jeopardize the co-existence of the two sectors, as each one operated in its own particular field.

Power market prospects indicated that this stability would gradually disappear and indeed it was suddenly broken by the recent increase in the cost of fossil-type power: the two sectors are no longer clearly separate. Competition between all forms of energy will dominate the energy system, owing to the new competitive aspect of electricity on the heating market. A change of this kind in the situation has serious consequences on the structures and internal organization of electric power producers. It also makes it necessary to re-examine completely the methodology concerning forecasts in the light of new conditions brought about by the increase in the use of electric energy.

In the present communication, it is proposed to illustrate in the first place how the methods used for forecasting requirements and programming were adapted to past growth conditions. Further on, an indication will be given of how they should be adapted to suit present conditions.

1. The Trend of Past Evolution

The strategy of the development of electric energy came within the context of fairly regular world economic evolution. The successive relay of specific uses comprising the particular field for electricity was also a regulating factor in the development of the total demand. The forecast demand could therefore be based on certain fairly clearly determined links between variables. On the other hand, the sustained rate of spontaneous demand induced firms producing, transporting, and distributing electricity to develop a strategy that merely accompanied this demand and satisfied its requirements. In this context, it was perfectly legitimate to consider that demand would develop exogenously.

It was therefore feasible to use forecasting models of the statistical type which took the essential of this evolution into consideration. By their very nature, they possessed the great advantage of enabling errors to be measured and a confidence level to be assessed. In these conditions, the forecasting methods were well adapted to the requirements of decision makers, in the terms of a fairly simple procedure --at least in principle--consisting notably in:

- defining the cost of failure; and
- combining supply with demand, both being random.

It could justifiably be maintained that this system led to the best possible definition of the volume of supplies required.

More analytical models were not excluded when required to satisfy requests for more specific information. However, without denying their utility, it must be stated that they only played a minor role.

1.1 Econometric Models

The various different econometric approaches possible all share a common characteristic: they all depend on the hypothesis that the structural relationships identified by observation in the past will be maintained in the future, in such a way that future identification of the explanatory variables retained is sufficient to determine the evolution of the endogenous variable.

As for the explanatory variables they may take different forms. They may consist of time alone (autonomous models). They may be other variables, such as a representative parameter of economic or industrial activity, the cost of electric power, demographic evolution, etc... (conditional models).

In a general manner, the various different possible approaches were tested. In practice, the models finally adopted--because they appeared to be the most pertinent under analysis--were fairly simple in form.

1.1.2 The Overall Approach

Its main interest lies in the simplicity of the hypothesis used. In effect, it implies that the mechanism of the growth of all electric power consumption (losses either included or excluded, varying with each case), considered as a whole, will remain unchanged, or, at least, that any changes in rhythm likely to affect them in the future will be mutually compensated for.

The most interesting model from this aspect is a conditional model of the adaptive type, in which the structural relationship retained is the link between increases in the total consumption of electricity, exclusive of losses, and increases corresponding to the gross internal production in volume. Losses are added afterwards.

For the period 1964-1973, the following equation is obtained:

$$\frac{\Delta C}{C} = \underset{(0.37)}{1.66}\,\frac{\Delta p.i.b.}{p.i.b.} - \underset{(2.13)}{2.68} + \varepsilon \qquad (R = 0.86)\ ,$$

where

$\frac{\Delta C}{C}$ represents the annual growth rate of the total consumption, exclusive of losses,

$\frac{\Delta p.i.b.}{p.i.b.}$ the annual growth rate of the p.i.b. in volume, and

ε a white noise .

1.1.3 Semi-Global Methods

Although attractive in itself, the simplicity of the hypothesis retained in the overall or global approach fails to make it possible to determine the diversity of the evolution--although confirmed--of the main components of the total demand. In particular, evolution in France over the last ten years has revealed a fairly marked difference in the growth rate between:

- the industrial sector, where consumption has developed at a moderate rate; and
- the agricultural sector, both domestic and tertiary, where the increase rate of consumption was clearly greater.

Under these conditions, it appeared necessary to explore the evolution of each of these demands by means of distinct models on the period 1964-1973.

$$\text{LOG } C = \underset{(6.0004)}{0.0998}\, t + \underset{(0.0163)}{4.0971}, \quad (R = 0.998)$$

proved to be insufficient to take the evolution of non-industrial consumption into consideration.

LOG C = Logarithm of the annual consumption of electricity in the agricultural sector, both domestic and tertiary,

t = time ($t = 0$ in 1974).

As for consumption in the industrial sector, it appeared that the variations in the volume of the added value in industry explained its evolution reasonably well. The model used then leads us to the following equation for the period 1964-1973:

$$\frac{\Delta C}{C} = \underset{(0.39)}{0.71} \frac{\Delta VAI}{VAI} + \underset{(2.5)}{0.70} + \varepsilon, \quad (R = 0.57)$$

in which

$\frac{\Delta C}{C}$ = the annual growth rate of the consumption of electricity in industry.

$\frac{\Delta VAI}{VAI}$ = the annual growth rate of the value added by industry, measured at constant prices, and

ε = a white noise.

As with the overall or global approach, losses are determined afterward.

The variance of total consumption is calculated by combining the variance of each component resulting from each particular model.

In the past, this semi-global approach confirmed the global approach fairly well, as the reference results coming from these different models produced relatively well grouped average figures for total medium-term consumption.

1.1.4 The Introduction of Elasticity to Power Prices

The models described up till now only use figures representing the volume of economic or industrial activity as explanatory variables. However, in the total demand, it was possible to discern several fairly diversified uses with respect to their technico-economic characteristics (high or low voltage supplies, load duration curve for each different use), and, in consequence, with respect to their price. Besides, these different prices did not necessarily evolve in a homothetic manner: for a firm applying a tariff policy reflecting costs, the component elements of the cost for each one of these uses were not necessarily the same, nor more generally affected by the same influences.

This analysis should logically lead us to question the existence of elasticities of consumption in relation to price and to measure them. However, the difficulties inherent in this kind of research work must be stated here:

a) as elasticity in prices of electricity could obviously not constitute the only explanation for the evolutions recorded, it was essential to define a structure of reputedly homogeneous uses in respect of a small number of parameters;

b) attention had to be given to the possible co-linearity between the various variables;

c) prices other than those for electric power could influence consumption development. If the price of combustibles could be neglected because of the partitioning of the energy market, the existence of a number of crossed elasticities was nevertheless conceivable: the price of electric household equipment, for example, for a large fraction of domestic consumption, or--and a relevant case will be seen later--the wages for certain industrial uses (mechanization of tasks);

d) some uses might prove to be sensitive to climatic conditions; and

e) finally, and in a more essential manner, supposing that it is possible to estimate elasticities with respect to prices, interpretation of results would never be very easy. The reason for this is that since the number of unit costs decreases with the quantities supplied, most of the tariffs applied are degressive with the quantities consumed by the user. So the existence of a link quantity versus price could just as well represent a characteristic of the supply curve as a characteristic of the demand curve.

Nevertheless, failing any very sensitive influence, calculations reveal significant but small links between prices and consumption.

For example, there is a connection between the evolution of consumption of electricity in industry for modulated uses (mainly motive power) and the relation between the price index for this type of electricity supplies and the hourly wages index, a connection improved by the introduction of a one year lag. The equation is as follows:

$$\frac{\Delta QHTM}{QHTM} = \underset{(0.12)}{1.11} \frac{\Delta p.i.b.}{p.i.b.} - \underset{(0.12)}{0.26} \frac{\Delta IPEW_{-1}}{IPEW_{-1}} , \quad (R = 0.85)$$

in which

QHTM = the modulated high voltage consumption,

p.i.b. = the gross national production in volume,

IPEW = the ratio electricity price versus hourly wages.

In the Appendix, a complete presentation of the results obtained for the four main operating categories will be found.

1.2. Analytical Models

There is a great temptation to push analysis further and to try to get a detailed breakdown of the consumption of electricity, by isolating, for example, each of the different branches of industrial activity, so as to discover the total consumption by means of summation.

Actually, one has to face many difficulties with this approach, for example, the multiplication of hypotheses on the development of each sector of activity; difficulties very quickly become insurmountable owing to combinations of different random variables. Finally, forecasts obtained by aggregation of partial results are essentially based on the present nomenclature of the branches. This nomenclature will inevitably be modified in the future as technical processes evolve. In consequence, one has to do without permanent statistical compensation which operates between expanding and declining branches without taking into consideration the successive relay between uses, which we have already discussed, and the "creative destruction," which, according to Schumpeter, can be identified with economic growth.

Must all types of analytical approach be rejected globally? Certainly not. First of all, these approaches give a possibility of crosschecking information, however imperfect it might be; on the other hand, they are essential in cases where specific information is required. As an example, let us note forecasts concerning the evolution of load duration curves, an element that cannot be disassociated from forecasts concerning power consumption, i.e. the necessity to localize future consumption inside a given territory.

Finally, analytical models are often likely to supply precious information for modifying, in one direction or another, the forecasts produced by econometric models. An illustration of this is supplied by an analysis test on increases in intermediate consumption of electricity (agriculture, industry, transport, tertiary sector) in three component parts:

1) varying like general economic activity;

2) linked to modifications in the weights of various branches of activity, which are caused by structural changes in the final demand; and

3) linked to the evolution of the technical coefficients in each branch and reflected in the consequences of the consumption of electricity of changes in production processes.

Studies of this type make it possible to quantify the incidences of electricity development due to alleviation of industrial structures: increases in the relative importance of light industries consuming little power at the expense of heavier industries; estimates of any accelerations that might be expected as a result of modifications to technical production processes; and in a more general manner, detection in good time of any new facts likely to influcence future consumption in a significant manner.

In conditions governing the growth of electricity in the past, as described above, the analytic approach only played an accessory role. The fact is that demand developed in a <u>regular</u> manner and exogenously placed econometric approaches in a favorable position. Uncertainties concerning the total were very limited and electricity producers could proceed to "adjust" their programs within a system where <u>stability</u> reigned (the term "adjustment" is furthermore significative in this connection).

2. New Conditions Governing the Growth of Electricity Consumption

For some little time now, however, signs of a new situation have become apparent. Faced with the medium- and long-term prospects concerning the prices of different types of power, producers of electricity expected that the partition separating the fossil energy sector and the electricity sector on the power market would gradually disappear. They had drawn an important conclusion: prospects concerning the cost and reliability of supplies made cost-effectiveness a rather fast development of nuclear power production. Nevertheless, this development would depend on a sufficient surge in the consumption of electricity, particularly in the heating market, which, as we have seen, has been reserved up till now for the fossil energy sector. Hence, a first decision: it is no longer enough just to follow demand; it becomes essential to take the appropriate commercial and promotional steps to activate this demand.

A decision of this kind, which announced the end of conditions in which demand was formed entirely exogenously, brought about an initial upset in the system: the notion of a structural invariant began to fade away. But it was nevertheless fair to assume that this would be gradual and temporary, as long as the growth of the demand is disturbed.

The considerable increase in the price of fossil energy has still further upset forecasting methodology. It means passing from a system with fixed frontiers to an open system, in which there is no "natural" limit to the expansion of electrical energy and which is dominated by the substitutability existing between different energy types. In the matter of power, economic choices have always been long-range choices. It is therefore up to government authorities to fix a medium- and long-term price on this market. Governments are capable of inducing present and future choices in conformity with the general power policy they intend to follow, particularly in making the necessary substitutions possible in the best possible conditions.

In so far as forecasting is concerned, inertia and time constants forbid the pure and simple abandonment of the methods used up till now. In the medium term, radical transformations can only have an effect on the system's margin, since everything that already exists constitutes, by its very nature, a more stable kernel which past decisions have shaped in a manner difficult to reverse.

On the other hand, in the long term, it is easier to dispose of the initial situation: the relative prices will be called upon to play a determining role, and, owing to the quasi-total substitutability between the different forms of power, distribution of the market is much more open. In this distribution, the massive advent of nuclear power will enable electricity to play an important role initially. For a longer term, though, other operating modalities must not be neglected.

The electricity sector, as regards both demand and production, is thus faced with new uncertainties, and, in order to remove uncertainties on the distribution of markets inside the power sector, one is inclined to "globalize" the problem. This globalization constitutes a radical breach of present forecasting methods: instead of a forecast for electricity, which is quasi-autonomous and which scarcely takes into account the interplay between the different forms of power, the extension of the problem aims at determining, on a national planning basis, the best possible distribution of the final demand for power.

An approach of this kind has not yet been formalized, but research work is beginning in this direction. It consists of the following: based on a forecast for final uses, without pre-determining the form or forms of energy to be used, the different chains are followed up to intermediate and primary forms of energy; the best possible distribution from the point of view of the community is then examined.

The criteria for estimating the best solution to a problem of this kind should be to take qualitative aspects into consideration, such as reliability of supplies of primary energy or external effects (nuisances). In so far as easily quantified aspects are concerned, it should be possible to take into account the various costs defining each chain:

a) the cost of supplies of fossil energy and nuclear combustibles;

b) investment and operating costs in the production process of electricity (and possibly of hydrogen) and costs involved in other processes for transforming fossil-type combustibles; and

c) finally, an important innovation in the approach suggested--investment and operation costs incurred by final consumers--depending both on the type of energy used and operating cost-effectiveness.

The main parameters governing the problem are as follows:

1) evolution of the cost of fossil-type and nuclear combustibles;

2) the results and cost-effectiveness of water electrolysis;

3) the cost-effectiveness and arrival date for hydrogen turbines;

4) the cost-effectiveness and arrival date of thermochemical water dissociation processes; and

5) the "asymptotic" levels of demand for different uses.

All of these are uncertain parameters, inducing us to look for an answer not in the form of one single decision, but in the form of a strategy dependent upon the realization of the various parameters.

The output of such a model would be the evolution of the demand for intermediate forms of energy (electricity, hydrogen, natural gas, petroleum products, heavy fuel, coal). Knowledge of these time series is essential to the producer of electricity: by providing the targets most suitable to the community's interests (meaning less waste), it can serve as a basis for:

a) its commercial policy, and

b) investment and production decisions.

It thus appears that new conditions governing the growth of the use of electricity mean that the problem of distribution of markets inside the complete power sector must be globalized. This entails a great change compared with previously used methods. This will indisputably require that, to a far greater extent than in the past, the conditions governing competition between the various forms of power will have to be examined with special attention. These conditions can only be appreciated if comparisons between complete chains are made, beginning with primary energy and extending to final use.

The field of this analysis will, from now on, be considerably enlarged. The future position of the power system itself within the whole economic system cannot be determined with any certainty and will depend to a very great extent on the behavior of the community and the policies adopted.

ELECTRICITY AND ENERGY SYSTEMS

Appendix

The Effect of Prices on the Demand for Electricity

Energy in general and especially under the elaborate form of electricity takes a great part in the economic growth of the developed countries.

The demand for electricity follows a very steady trend in the medium range (it doubles approximately every 10 years); but this trend goes with a diversified growth of the different uses of electricity. When one tries to point out the effect of prices on electricity demand, one meets two kinds of difficulties, due:

- first to the necessity of defining a homogeneous repartition between the uses; and
- secondly to the dependencies between most of the explanatory variables.

1. Methodology

1.1 Structure of Uses

Four uses are distinguished:

1) lighting and domestic uses;

2) motive power for industry;

3) electrolysis and specific industrial uses; and

4) integrated electric heating.

The statistical data available lead often to oversimplification. One can consider that the first usage corresponds to the low voltage demand, even though one finds motive power in the low voltage sales and lighting in the high voltage. The second type ("industrial modulated demand") is defined as the residual part of the high voltage sales. The third type ("flat uses") covers industrial sectors characterized by a rather regular load duration curve. One must consider the demand for the fourth use as negligible in the past.

1.2 Dependent Variables

To build a multivariable explanatory model for the electricity demand, one meets problems due to the fact that most of the explanatory variables (GNP, industrial added value, household consumption, electricity prices, general level of prices, wages...) are not independent.

This leads to consideration of the rates of growth and not the absolute levels of the different variables.

2. Explanatory Variables

Use (1)

The growth of the low voltage demand is in relationship with the number of consumers (i.e. practically the size of the population) and with the household equipment. It seems that the utilization of new household equipment is responsible for the growth of the demand, so that one may retain household consumption as an explanatory variable. So far as one considered that the operating cost of electro-domestic equipment had no effect on the buyers' decisions, the actual growth of low voltage demand is weakly correlated with tariff increases (real and nominal). The partial correlation coefficients are respectively .19 and .48, and the correlation may be improved by considering a moving average of deflated increases over 2 or 3 years. This refers implicitly to a behavior which would adapt itself to the past tendency of prices.

Weather severity is the last explanatory variable introduced because of its effect both on extra heating and on luminosity (hence on lighting uses).

Use (2)

As for low voltage sales, the evolution of motive power uses in industry may be related, in the medium term, to the substitution of capital goods for labor, although there may be fluctuations in the rate of utilization of production capacities. As a matter of fact, one may point out a relationship between the deflated price of electricity and the relative price of electricity vs. wages. The correlation is introducing a time lag of one year for prices.

Use (3)

For a certain number of uses gathered in this group, electricity has no practical substitute (e.g. for aluminium production), and is often a determinant part of production costs.

There is actually a strong correlation between the production of the different sectors involved and their demand for electricity. One must of course take into account technical progress which tends either to increase or to decrease the specific consumption (e.g. steel or aluminium).

A decreasing trend in the rate of growth of this third use is due to international competition: one may observe in this type of big electricity consumer a tendency to look for new locations in areas where both mineral resources and electricity are cheap and abundant.

Apart from the GNP, the best explanatory variable is the nominal index of high voltage electricity prices.

3. Results

The statistical data cover the period 1952-1972. All the regression coefficients are one non-zero at the level of significance of 5 per cent. Durbin and Watson's coefficients are also satisfactory.

Use (1)

Variables:

QBT : Low voltage consumption (in TWh)
ICM : Index of household consumption, in volume (1,000 in 1952)
IPRBT : Index of real prices for low voltage sales (1,000 in 1952)
ITBT : Index of low voltage tariff
CRC : Weather severity coefficient

$$IPMBT_{012} = \frac{1}{3}\left[IPRBT + IPRBT_{-1} + IPRBT_{-2}\right]$$

$$IPMBT_{01} = \frac{1}{2}\left[IPRBT + IPRBT_{-1}\right]$$

$$IPMBT_{12} = \frac{1}{2}\left[IPRBT_{-1} + IPRBT_{-2}\right]$$

$$\text{Log QBT} = 1.85 \quad \text{Log ICM} - 3.94 \qquad (R = 0.999)$$

$$\frac{\Delta QBT}{QBT} = 0.63 \frac{\Delta ICM}{ICM} + 8.3\ \Delta CRC + 6.26 \qquad (R = 0.71)$$

$$\frac{\Delta QBT}{QBT} = 0.56 \frac{\Delta ICM}{ICM} + 8.4\ \Delta CRC - 0.06 \frac{\Delta IPRBT}{IPRBT} + 6.53 \qquad (R = 0.71)$$

$$\frac{\Delta QBT}{QBT} = 0.36 \frac{\Delta ICM}{ICM} + 7.9\ \Delta CRC - 0.66 \frac{\Delta IPMBT_{012}}{IPMBT_{012}} + 7.02 \qquad (R = 0.80)$$

$$\frac{\Delta QBT}{QBT} = 0.18 \frac{\Delta ICM}{ICM} + 8.0\ \Delta CRC - 0.48 \frac{\Delta IPMBT_{01}}{IPMBT_{01}} + 7.96 \qquad (R = 0.82)$$

The best regression is:

$$\frac{\Delta QBT}{QBT} = \underset{(0.19)}{0.58} \frac{\Delta ICM}{ICM} - \underset{(0.17)}{0.39} \frac{\Delta IPMBT_{12}}{IPMBT_{12}} + \underset{(2.6)}{8.7}\ \Delta CRC + \underset{(1.0)}{6.11} \qquad (R = 0.82)$$

Use (2)

QMTM : Modulated high voltage consumption (in TWh)
IPIB : Index of the gross internal production in volume
IPRHT : Index of the real prices of high voltage supplies
IPEW : Index of the relative prices electricity vs. wages

$$\text{Log QGTM} = 1.29 \quad \text{Log IPIB} + 2.73 \qquad (R = 0.9987)$$

$$\frac{\Delta QHTM}{QHTM} = 1.33 \frac{\Delta IPIB}{IPIB} \qquad (R = 0.78)$$

$$\frac{\Delta QHTM}{QHTM} = 1.11\ \frac{\Delta IPIB}{IPIB} - 0.25\ \frac{\Delta IPEW}{IPEW} \qquad (R = 0.82)$$

$$\frac{\Delta QHTM}{QHTM} = 1.22\ \frac{\Delta IPIB}{IPIB} - 0.38\ \frac{\Delta IPRHT}{IPRHT} \qquad (R = 0.83)$$

$$\frac{\Delta QHTM}{QHTM} = 1.31\ \frac{\Delta IPIB}{IPIB} - 0.24\ \frac{\Delta IPRHT_{-1}}{IPRHT_{-1}} \qquad (R = 0.84)$$

The best regression is:

$$\underset{(0.12)}{\frac{\Delta QHTM}{QHTM} = 1.11}\ \frac{\Delta IPIB}{IPIB} - \underset{(0.12)}{0.26}\ \frac{\Delta IPEW_{-1}}{IPEW_{-1}} \qquad (R = 0.85) \quad .$$

Use (3)

QUP : "Flat" uses (in TWh)
IPIB : Index of the gross internal production in volume
ITHT : Index of the high voltage tariff (1,000 in 1952).

$$\text{Log } QUP = 1.095 \quad \text{Log } IPIB - 4.60 \qquad (R = 0.984)$$

$$QUP = 14.96 + 2.14\ (t - 1952) \qquad (R = 0.998)$$

$$\frac{\Delta QUP}{QUP} = 1.10\ \frac{\Delta IPIB}{IPIB} \qquad (R = 0.46)$$

$$\frac{\Delta QUP}{QUP} = 1.85\ \frac{\Delta IPIB}{IPIB} - 0.40\ (t - 1952) \qquad (R = 0.76) \quad .$$

The best regressions are:

$$\frac{\Delta QUP}{QUP} = \underset{(0.46)}{1.60}\ \frac{\Delta IPIB}{IPIB} - \underset{(0.003)}{0.010}\ ITHT + \underset{(4.15)}{10.18}$$

(R = 0.73)

$$\frac{\Delta QUP}{QUP} = \underset{(0.43)}{1.32}\ \frac{\Delta IPIB}{IPIB} - \underset{(0.044)}{0.218}\ QUP_{-1} + \underset{(2.78)}{6.76}$$

(R = 0.81)

4. Conclusion

In the past the effect of prices may be considered as rather weak. However studies in terms of elasticities can be undertaken, keeping in mind that their conclusions are very uncertain.

Discussion

One of the participants asked if the population growth had been taken into account in the model. Mr. Janin answered that this is done by the number of households.

Mr. Styrikovich (USSR) asked if the electricity demand for house heating comes from resistance heating. Mr. Janin replied that they are just at the beginning of a study to find out the best system for electrical heating. In this study resistance heating and also off-peak resistance heating during the night are possibilities which are considered. Finally, he remaked that a good insulation is one thing which is important for each of these systems, and the French government published insulation norms which have to be satisfied by new buildings in 1978. Then Mr. Styrikovich commented that they do not want to increase the demand for electricity; thus they use central heating which relies on thermal energy from central electric power stations. Mr. Janin agreed from a theoretical and physical point of view but pointed out that the regulation of thermal energy is very complicated due to the loss during the transportation; sometimes more thermal energy is delivered to the final consumer than is actually needed and the only way to manage it is to open the window. Then he mentioned a French study about electrical heating combined with good insulation and regulation of central heating where the total demand for energy comes up to be almost the same in both cases.

Another delegate made two comments: First, he suspected that it is very important to find out the right relation between GNP and the energy demand. Secondly, he stressed that it seemed to him that energy has to be used more effectively, and the one and only way in which he thought that this could be done was to change the philosophy of low price energy supply to an optimal price strategy, which means that the price has to be used to control the energy demand. Mr. Janin agreed and mentioned a study of the French government wherein they changed the coefficients of many sectors in order to obtain a more efficient use of electricity. Then this delegate argued that one has to find strategies to change the structure of the economy. Mr. Janin agreed and remarked that many years ago France had a very high energy price and people were guided by high efficiencies at that time.

Mr. Krymm (IAEA) asked what kind of criteria they would use in a supply model to get the electricity demand changed from an exogenous to an endogenous variable. Mr. Janin answered that the energy cost for the final consumer is the best criterion but they do not know as yet what the cost function is.

A Comparison of Mathematical Models for Long-Term Planning of the Economic Operating and Extension of a System of Power Stations

G. Modemann and P. Winske

1. Introduction

The aim is the sufficient, reliable and cheap supply of electrical energy taking care of the environment. That means a technical and economic task concerning the whole expected life time of the next plants that are going to be installed and whose external conditions are changing. These large investments need aids for decision making.

For this purpose methods of Operations Research have been developed in the 1950s and 1960s which require large and fast digital computers. The task comprises the following structure:

Step 1. analysis of the system electricity company or public electricity supply;

Step 2. mathematical description and finding of data;

Step 3. model construction, i.e. a logical-mathematical construction;

Step 4. simulation of the behaviour by means of OR algorithms;

Step 5. interpretation of the results.

The most important problems are:

1. quantification of the objective function, that is the forecast and finding of weights for partial aims in terms of costs;
2. quantification of restrictions, that is forecast and finding of technical and economic limits; and
3. finding suitable methods of optimisation. To dodge into parameter studies does not mean that one does not have to make decisions.

2. Description of the three models and optimisation methods used

Comparison of the three principal different models as far as methods and results go:
In the first two models (LP Linear Programming and NLP Nonlinear Programming) the variables are continuous, in the third (DP Dynamic Programming) they are discrete. A model with mixed integer-continuous variables has been started but this will not be discussed today.

2.0 What the three models have in common:
All three are zero dimensioned or point models which means one takes for granted the ideal operating of the power plant system without elements of energy transfer.
In [4] the high-tension mains of the German Federal country North-Rhine-Westfalia were included in order to get an optimisation of the plant location within the frame of the installation problem. This was only possible in a model with discrete variables.

2.0.1 Analysis and forecast of quantity and characteristic of the electric energy demand. In these programs they are calculated in separate sub-programs.

2.0.1.1 Quantity. For the models LP and NLP the demand of the FRG is forecasted in a global way, basically dependent on consumption per person [Fig.1 and 2]. For the model DP the demand was determined according to forecasts by sectors e.g. industry, household, commercial, etc. This, however, was not influenced by the method DP.

2.0.1.2 Characteristic. The common ordered annual load diagram can hardly be used, for example, because the peak load in summer is identified with the lower medium load in winter. This is wrong for installation problems because even in the future the planned shut down periods should lie in the months of low load. Because of this the daily generating diagrams were used, namely workday, Saturday, Sunday, for a typical month of each season of the year; that means 12 diagrams for a basic year. The change of shape of the daily diagrams was forecasted for the planning horizon. After certain substeps, which are different for the three models, a demand of power was found [Fig.3 and 5] divided in load sections, i.e. ordered annual generating diagrams.

2.0.2 Technical and economic parameters for the calculation of energy production costs which influence the result fundamentally and which are identical for the three models as far as possible for the comparison in Chapter 3. The following parameters are all dependent on time.

2.0.2.1 Technical parameters: For LP and NLP, average value of electric net power of units of each type; efficiency; calorific value; burn-up of nuclear power plants.

2.0.2.2 Economic parameters: direct and indirect costs of installation, life time of plant, rate of interest, operating and maintenance costs, fuel costs; the calculation of the nuclear fuel cycle costs is done in a separate computer program.

2.0.2.3 Energy-production costs in fixed and variable portions. The fixed costs are only dependent on the type's installation capacity. The costs of investment for those power plants which were existent before the planning horizon were not taken into account because they do not influence the result of optimisation.

The variable costs only depend on the quantity of energy which is produced by the existent and newly installed power plants.

Both fixed and variable costs are discounted at the beginning of the planning horizon in order to be able to compare costs at all, in the following marked *

With all models optimisation means minimisation of the total energy-production costs.

2.0.3 Restrictions can be divided in two groups:

1. Restrictions which necessarily result from the general character of the planning task or from the structure of the model.
2. Restrictions which can be used in order to take account of special conditions in case of certain planning problems, among others: a) maximum or minimum energy of a type, e.g. coal; b) minimum or maximum capacity of a type, e.g. nuclear power plants of the second generation; c) nuclear fuel balances, e.g. plutonium.

Reserve capacity: When giving longterm forecasts of energy demand it does not seem sensible to consider short term differences. For the calculation of the necessary reserve power the random failure is estimated for the time of the annual peak load. In a special program a reserve capacity of 11-12% of the annual maximum power was calculated [5].
As run-off-the-river power plants have to be treated specially they are not mentioned in this paper although they are included in the models.

2.1 Linear Programming (LP) [1]

In this model optimal decisions were calculated for every year of the planning horizon. It is the condition of LP to grant only linear forms of the variables.

2.1.3.2 Restrictions in power and energy of single types of power plants.

(a) disassembly ΔA_i of power plants $P_i(t) \geq P_i(t-1) - \Delta A_i(t)$

(b) power restrictions: $P_i(t) = \sum_{j=1}^{NJ} \frac{e_{i,j}(t)}{T_o n_j(t)} \leq L_i(t)$,

breeder reactors for example.

(c) minimum consumption of fuel-type, for example hard coal

$$\sum_{j=1}^{NJ} e_{i,j}(t) \leq E_i(t)$$

2.1.4 Example.

To conclude, Fig. 4 shall illustrate the kind of results which are essentially determined by the input data. It shows the optimal distribution of the net electricity production and the maximum net capacity in West Germany until the year 2000.

2.2 Non-linear programming (NLP) [2]

As opposed to the model talked about in .1, in this model it was not the aim to find out a sequence of optimal partial decisions but to minimise the overall costs K* which are summed up in the whole planning horizon. In order to minimise the objective function a method of general convex optimisation is used.

Because of this, the power areas in the annual diagram are portioned in rectangular sections.

2.1.1 Annual generating diagram.

On the basis of the daily diagrams (2.0.1.2) utilisation factors n_j are found out for each load section, whose power portions of the maximum net capacity are calculated by dividing quantity of energy E_j by n_j. See equation:

$$\frac{1}{T_o\ P_{max}}\left[\frac{E_1(t)}{n_1(t)}+\sum_{2}^{NJ}{}_j\ \frac{E_j(t)}{n_j(t)}\right]=1+P_{res}\quad .$$

As shown in the annual generating diagram in Figure 3 the utilisation time in the second load shape is augmented by adding the pumping energy because the base load range is filled up by definition to its technical limit. After the loss is subtracted, the pumping energy generation of thermal power plants is allocated in the peak load (the hatched areas in Fig.3).

2.1.2 Objective function.

Variable $e_{i,j}(t)$ Quantity of energy of type i in the load section j in the year t |MWh/a|

Coefficient: $kfix^*_{i,j}(t) + kvar^*_{i,j}(t)$: specific generating costs of the type i in the load range j in the year t |DM/MWh|

$t_a \le t \le t_e$ planning horizon; NJ = number of load ranges

NW (number of thermic plant types) + NP (number of pumping storage types = 1) = NI (number of all power plant types).

Now the objective function:

$$Z(\vec{e}) = \sum_{t=ta}^{te} \min_{e_t} K^*(\vec{e}_t) = \sum_{t=ta}^{te} \min \sum_{i=1}^{NI} \sum_{j=1}^{NJ} \left[kfix^*_{i,j}(t) + kvar^*_{i,j}(t)\, e_{i,j}(t) \right].$$

to minimise the power production costs $K^*(\vec{e}_t)$ in [DM/a]. There are also models whose total costs are minimized in the objective function within the planning horizon, e.g. [6].

2.1.3 Restrictions.

2.1.3.1 Energy balances for every year t without the second and last load section (NJ - 2):

$$E_j(t) = \sum_{i=1}^{NW} e_{i,j}(t)$$

2nd load section:

$$E_2(t) = Ekorr_2(t) - \frac{1}{\eta_{pt}} e_{NI,NJ}(t) \qquad Ekorr_2(t) \le \frac{n_1}{n_2} E_2$$

last load section NJ:

$$E_{NJ}(t) = \sum_{i=1}^{NW} e_{i,NJ}(t) + e_{NI,NJ}(t)$$

That is because the objective function as well as the restrictions depend partially on the variables of a non-linear kind. Of all the known methods for solving convex optimisation problems the CRST method of [7] seems to be the most efficient one. Its main thought is transferring the restricted minimisation problem to an unrestricted one. The method SUMT of FIACCO-MCCORMIC [8] was used with a little adaptation.

2.2.1 Annual generating diagram.

The necessary convexity can only be given if you have a monotonously falling load shape in this diagram [Fig. 5]. It consists of several trapezoid-shaped load sections whose contents of energy have been found out as in 2.1.1. With this, however, the maximum and minimum power and utilisation time of the basic daily diagrams limit the sections' base load and peak load. The two medium load sections have to contain the quantity of energy that was found out. What was said in 2.1.1 applies analogously to the hatched areas of pumping energy.

2.2.2 Objective function.

Variable $X_{i,j,p}$ Power of type i in the load section at the end of period p |MW|

Coefficient: kfix* $_{i,p}$: specific fixed costs of the type i installed in period p caused in the remaining time horizon |DM/MW|

$kvar^*_{i,j,p}$: specific variable costs of the type i in the load section j, caused in period p, |DM/MWh|.

It is sensible as far as economy goes, and for the convexity of the objective function necessary, to insert the plant types in the diagram in the sequence of increasing specific variable costs [Fig. 5].

Now the objective function:

$$\min_{\vec{x}} K^* (\vec{x}) = \mathrm{Min} \sum_{1}^{NP} p \sum_{1}^{NI} i \{ kfix^*_{i,p} (A_{i,p} + \sum_{1}^{NJ} (x_{i,j,p} - x_{i,j,p-1})) + \sum_{1}^{NJ} j \; kvar^*_{i,j,p} \cdot x_{i,j,p} \cdot T_{i,j,p} \}$$

$$\text{with} \quad T_{i,j,p} = T_{L\;j+1,p} + \frac{T_{L\;j,p} - T_{L\;j+1,p}}{P_{L\;j,p}} \left(\sum_{1}^{NIJ} \ell \; x_{\ell,j,p} + \frac{x_{i,j,p}}{2} \right)$$

In these formulae there are pure and mixed quadratic forms of variables. The complete production costs K* which come up in the planning horizon consist of two parts: The first depends on the new installed capacity; the second on the produced quantity of energy in the generating diagram. To limit the maximum number of variables N = NI • NJ • NP, the planning horizon was divided into periods p (here - 30 years into six periods). Within each period one considers a continuous progress between the status of the beginning and the end of the period.

2.2.3 Restrictions.

First of all as opposed to 2.1.3 one has to satisfy power balances

$$\sum_{1}^{NI} i \; x_{i,j,p} \geq P_{L\,j,p} \text{ for } j = 1 \cdots NJ \text{ and } p = 1 \cdots NP \quad .$$

With the ordered insertion of plant types the energy balances had been satisfied. The pumping storage type is treated analogously as in 2.1 and the restrictions are similar to those in 2.1.3.

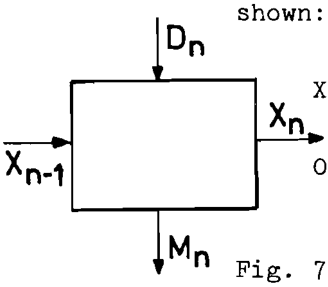
2.2.4 To conclude, Fig. 6 shall illustrate again the optimal distribution of the net electricity production and the maximum net capacity in West Germany until the year 2000.

2.3 Dynamic Programming (DP) [3,4]

In this model, for a medium term, a sequence of decisions to install new blocks will lead to a minimum of electricity production costs. Its planning horizon (for example 10 years) which is short compared to the other models seems to be sensible because of the micro structure. This method is based on BELLMAN's optimisation principle [9].

2.3.1 Explanation of method:

The divisibility of the system in steps is essential for DP because the calculation effort is growing exponentially with the number of variables but only linearly with the number of steps. Such a step with one decision variable and one state variable is shown:



$$X_n = t_n(X_{n-1}, D_n) \text{ for } n = 1 \cdots N$$

Obj. function: $f_n(X_n) = \min\limits_{D_n}(r_n(X_{n-1}, D_n) + f_{n-1}(X_{n-1}))$

Fig. 7 illustrates this method: Starting from an initial state point X_o only the optimal path back to X_o will be selected for every allowable state point in every step. After one has reached the last step N, from every final state point the sequence of decisions which is overall optimal can be named.

2.3.2 Objective function.

Decision variable xi_n:	block power of the type i in the period n |MW|
state variable P_n:	power in period n |MW|
grid:	ordinate state variable P_n, abscissa period n
coefficient:	$kfix^*_n$ (xi) specific fixed costs in the period n for an extension decision xi (DM/MW)

$$Z_n(P_n) = \min_{xi_n} \{K^*(P_{n-1}, xi_n) + Z_{n-1}(P_{n-1})\}$$

$$\text{with } K^*(P_{n-1}, xi_n) = \sum_{1}^{n-1} {}_{nj} \underbrace{\{\Delta t_{n,j} \cdot \hat{x}_{nj} \cdot kfix^*_{n,j}(\hat{x}_{nj})\}}_{a} + \underbrace{\Delta t_n \cdot xi \cdot kfix^*_n(xi)}_{b}$$

$$+ \underbrace{Kvar^*_n(P_{n-1} + xi_n, TD_n)}_{c} \;.$$

The discounted costs K* of every period n consist of three terms:

a) the fixed costs caused in period n from the blocks $\hat{x}_{nj}$ which had been newly installed since the start of the planning horizon;

b) the fixed costs caused in period n from the decision to install the new block xi_n;

c) minimum variable costs of the operating plants with the total power $P_{n-1} + xi_n$ in the daily diagrams of the period n.

2.3.3 Restrictions.

The balances of energy and capacity which were named in 2.1.3.1 and 2.2.3 have to be satisfied. Special restrictions are as analogous as possible to 2.1.3.2 and 2.2.3.

2.3.4 Results and example.

The insert optimisation has to be done for every path in every step and should only last a short

execution time. For this in [3] a modified branch and bound method of DP has been developed. In a bicentric tree two blocks respectively form a new fictitous block on the next level considering their allowable operating states; the new fictitious block allots the power optimally to the real blocks under all possible discrete loads. For the insert optimisation tion of the thermal plants the daily diagrams are planned according to figure 8: the expected portion can be determined in a more detailed way with the hydrothermal insert optimisation or the basis of the results of the thermal insert optimisation.
To conclude, Fig. 9 demonstrates the optimal distribution of the net electricity production and the maximum net capacity for the federal country North-Rhine Westphalia from 1972 to 1981.

3. Comparison of the three models

3.1 Results

To get comparable results for the three models it is very important that:

1. the data input are as equivalent as possible
2. the intended limitations of the range of possible solutions are realized as equivalent as possible by means of the restrictions of the models.

The discussion of the results is limited to the differences which were caused by the models.

3.1.1 Case LP - NLP [10]

The results of this case of comparison are explained with the help of figure 10 and 11 showing the optimal shape of power in West Germany until the year 2000. A great difference is noticed in the shape of time of the oil and nuclear power. With LP the LWR is strongly installed and from 1985 its power remains constant whereas the oil power is decreasing steadily. With NLP the power shape shows the same tendency but its level of power is halved. The oil power is increasingly installed from 1975 to 1985 and from then on to the year 2000 its portion is decreasing strongly but stays considerably above the reference level. The contrary extension with NLP has the following reasons:

1. Integral optimisation with which restructuring of insert of power plants which occurs later is taken into consideration from the beginning.
   a) The electricity production costs of the oil power will be lower from 1995 on than those of the LWR with a utilisation factor n = 0,85.
   b) From the newly installed nuclear capacities of the second generation in later years the LWR is going to be shifted to the medium load section.

2. Improved simulation of the insert of plants with help of the trapezoid generating diagrams. With the shift of plants from one section to another one gets a continuous alteration of the utilisation time, i.e. the costs, whereas with the LP there is only a salient alteration of the utilisation time, which is why the oil power will have a lower portion in 1980 and why the LWR has a larger share with LP. In LP the known rectangular shape of generating diagrams is used and the result is a consideration of pumping storage which is not totally representative, because all plants of the second load section take part in the generating of pumping energy but their share is not a result of variable costs as with the NLP. Because the mixed costs of the pumping energy are higher in LP, fewer pumping storage plants are installed. This tendency can be seen in the figures but it should be noted that the lacking peak load is produced by the GT.
   On the other hand, in NLP the pumping storage power comes off too well because in this case it is pretended that the cheapest power plants of the 2nd load range supply the largest quantity of pumping energy. However, a free capacity

of these plants is taken for granted which in reality should not exist. The result of all this is in NLP, the pumping storage plants have too low variable costs and come off too well in the competition with GT. Probably, the real increase of capacity of PS will be lower than in NLP but still higher than with LP.

3.1.2 Case NLP - DP [11]

Considering the federal country North-Rhine Westfalia of West Germany and a planning horizon of ten years, in figures 12 and 13 the shape of time vs. power and energy of the single plant types is shown. In the DP results the single power plants are drawn together into types. The results of both models coincide remarkably, only the portions vary. In both models the increase of power is supplied by LWR but the DP share is larger. That results from

1. step-wise optimisation which can take integral effects into account only under certain conditions;
2. the more detailed consideration of load shape by means of characteristic daily diagrams;
3. blockwise consideration which makes it possible that the variable costs of each block can be considered as a function of the inserted power.

Therefore in the NLP the integral effect of the optimisation is exclusively a result of shifting single plant types in higher load ranges during the planning horizon. The cost data stay constant in the planning horizon and the normalised generating diagrams show hardly any change at all. Towards the end of the planning horizon the shifted plant types produce more energy with NLP than with D as shown in fig. 13. So, in NLP for the LWR only a smaller portion of energy is remaining. This again leads to an increase of its power. Towards the end of the planning horizon the GT shows a strong increase of capacity in NLP and the reasons are probably the inaccuracies in the consideration of peak load and the faults caused from breaking up the calculation.

3.2 Data and computation effort

1. Effort for finding and processing of data.
   It is roughly the same in both continuous models and the amount of data is still easy to survey. For the discrete model the amount of data and the effort increase rapidly because of the necessary micro structure.
2. Computation effort.
   The calculations for all models were executed on the CDC 6400 of the Rechenzentrum der RWTH

Aachen, which has a maximum core capacity of 96K. The core storage and execution time for the examples given in chapter 2 can be seen in table 1.

3.3 Criteria for the distinction of the three models

Table 2 summarises the characteristics of important points of view.

These criteria may be helpful for a user in order to find the appropriate method for his problem. Commercial questions or matters of public planning can play a decisive role. The industrialist is mainly interested in medium term micro structured results which concern his control and decision periods. The public planning on the other hand needs mainly macro structured results which integrally take into account the interdependence in the whole planning horizon.

If the models are judged according to the essential interests of the two groups of users one can see the following clearly.

The DP model seems to be suitable mainly for commercial purposes. For public planning the NLP model seems to be the better one. The LP model seems to be mainly one for long term planning employed by commerce. This is our recommendation. Note, however, for users' special problems an altered recommendation might be more suitable [§.3].

4. A new frame of our studies is our working in common with other groups in a project of the Ministry of Research and Technology of the FRG with the title "Forecasting the electric demand as a function of economic and social development and its supply with the help of nuclear power".

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[1] Rheinisch-Westfälische Technische Hochschule Aachen
Institut für Elektrische Anlagen und Energiewirtschaft
Lehrauftrag Leistungsreaktoren

Abbreviation

General

A = Energy

a_p = Pumping Energy

k_s = Energy generation costs

P = Power

$T_{l,j}$ = Utilisation Time of the Load Range j

V = Electric Energy per Capita and Year

$X_{i,j}$ = Power of One Plant Type in the Load Range j. In each load range the plant types are arranged with decreasing variable costs.

Plant Types

BK = Lignite

EG = Gas

GT = Gas Turbine

HTR = High Temperature Reactor

LW = Run-of-the-River Station

LWR = Light Water Reactor

Öl = Oil

PS = Pumping Storage Station

SBR = Fast Breeder Reactor

SK = Hard Coal

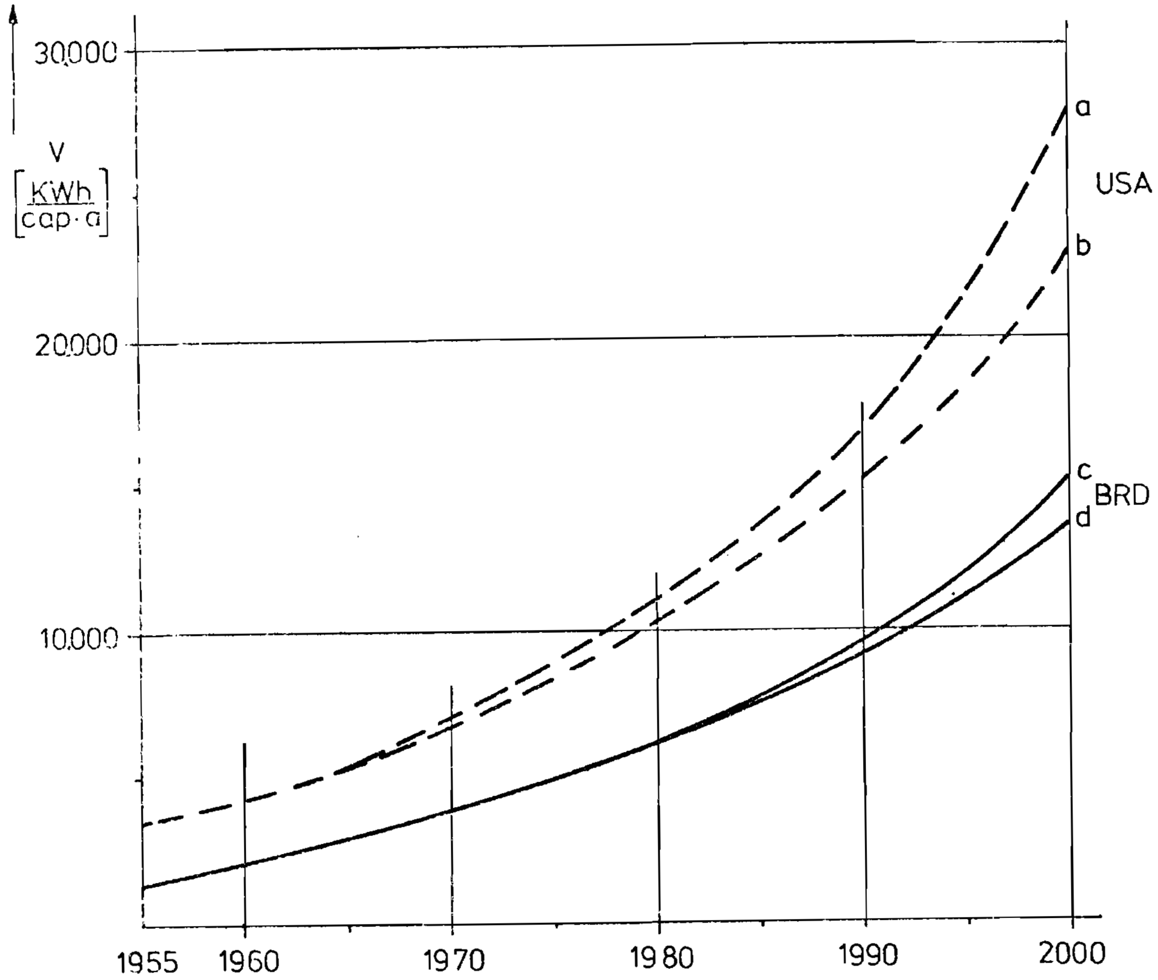


Fig.1: Forecast for Per-Capita-Electric-Energy Consumption

Legend: a) Federal Power Commission c)
b) Scher, G.B., AIEE Winter Meeting 1962 d) } FRG

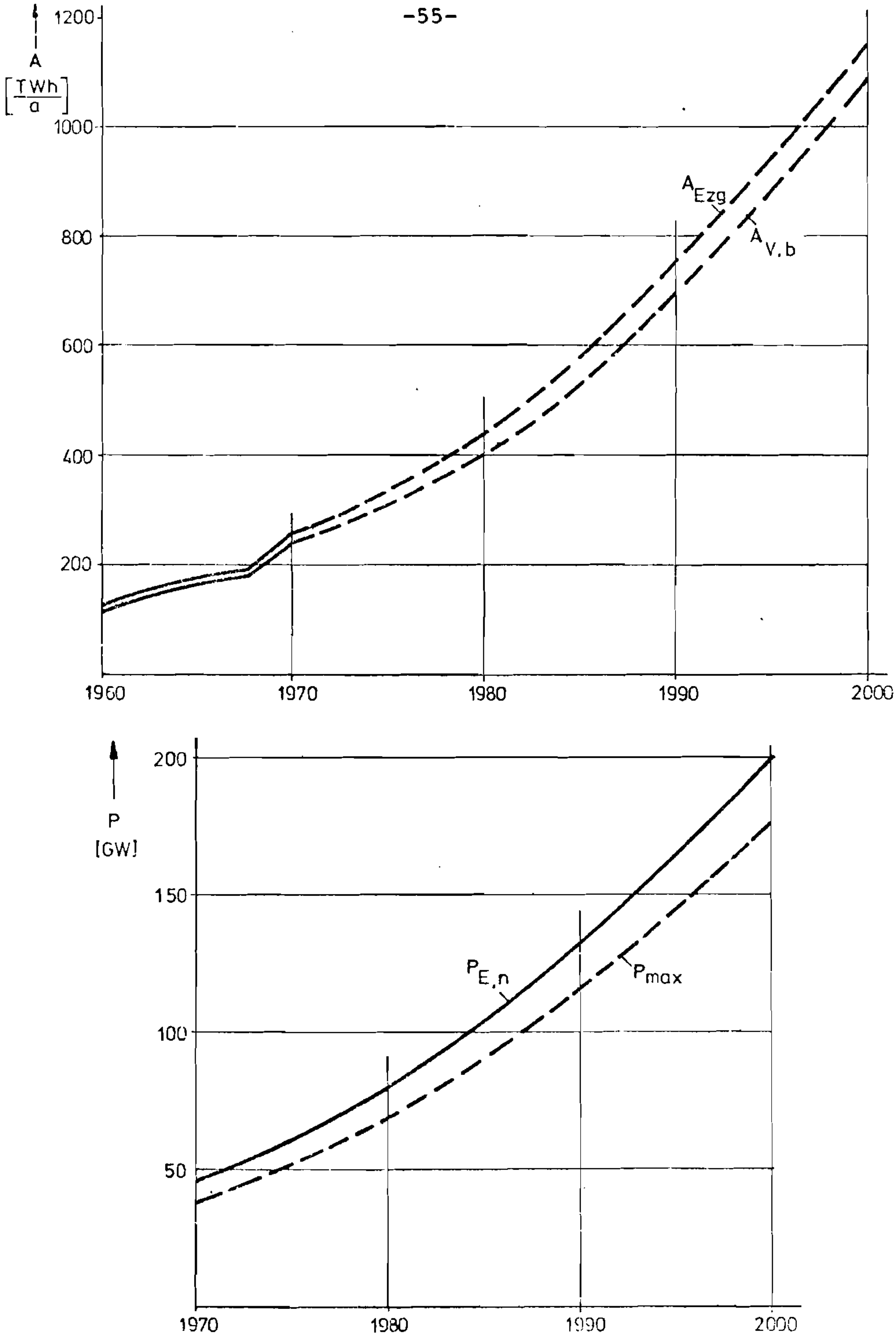


Fig.2: Possible Growth of Electric Energy and Power Demand

Fig.3: Linear Programming

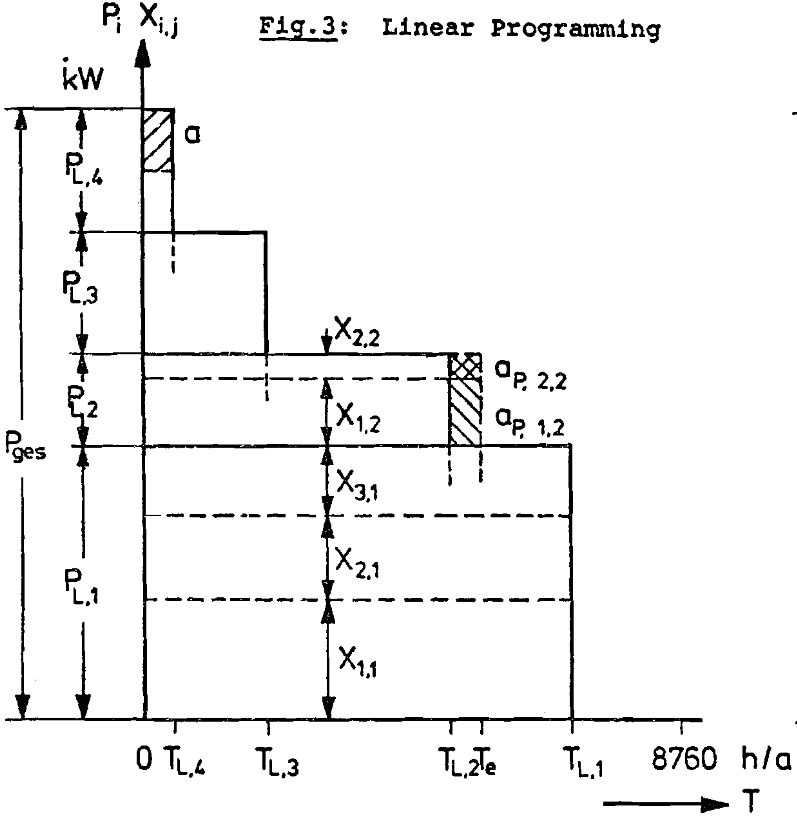
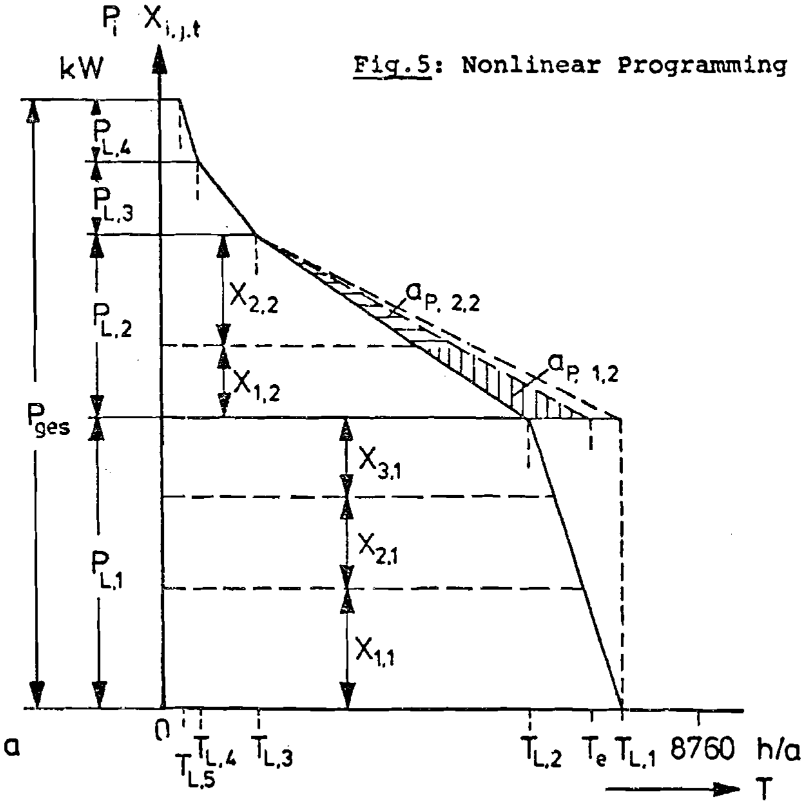


Fig.5: Nonlinear Programming



Insert of Power Types in the Generating Diagram of the Year t

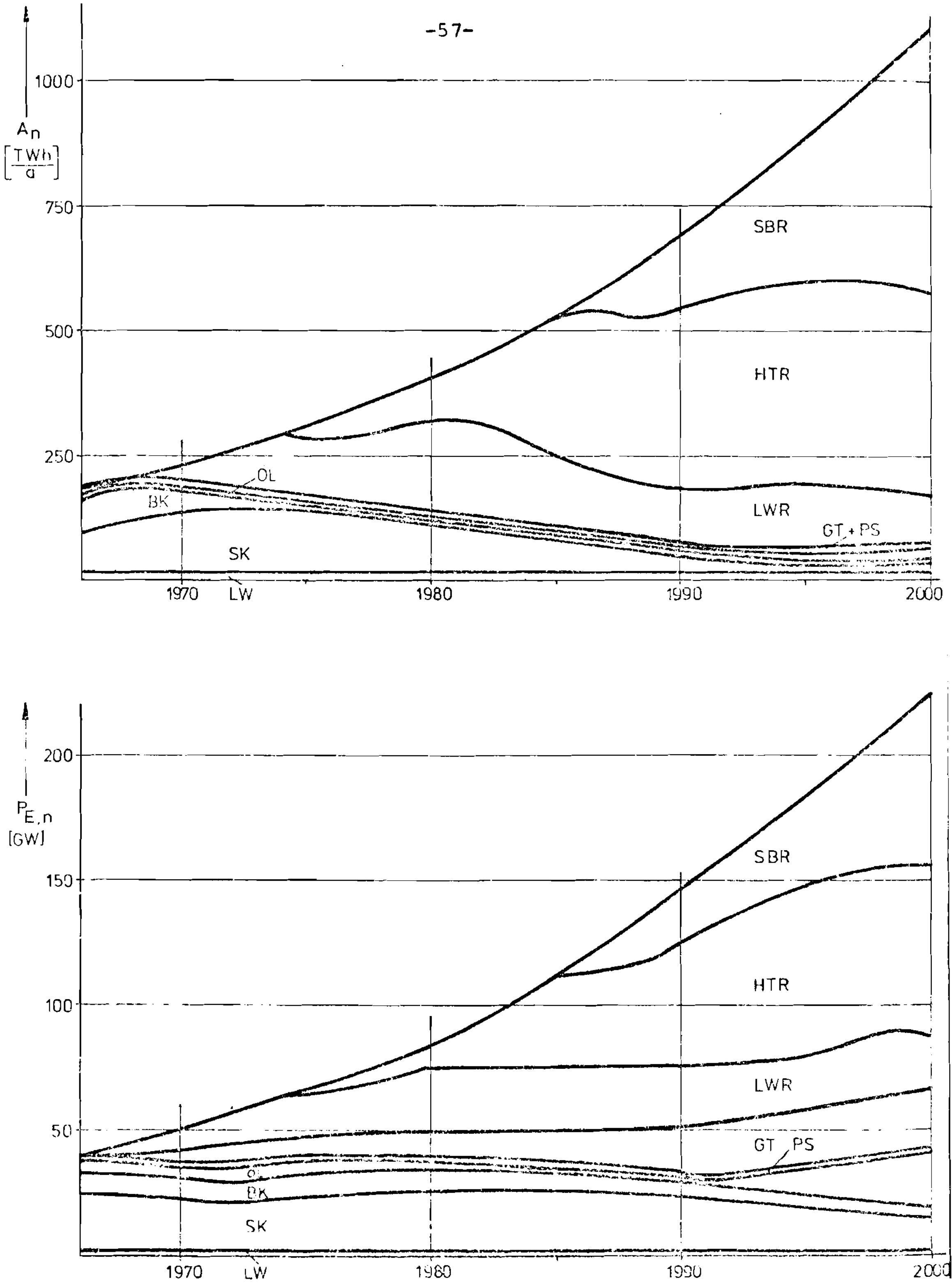


Fig.4: Example 1: Linear Programming

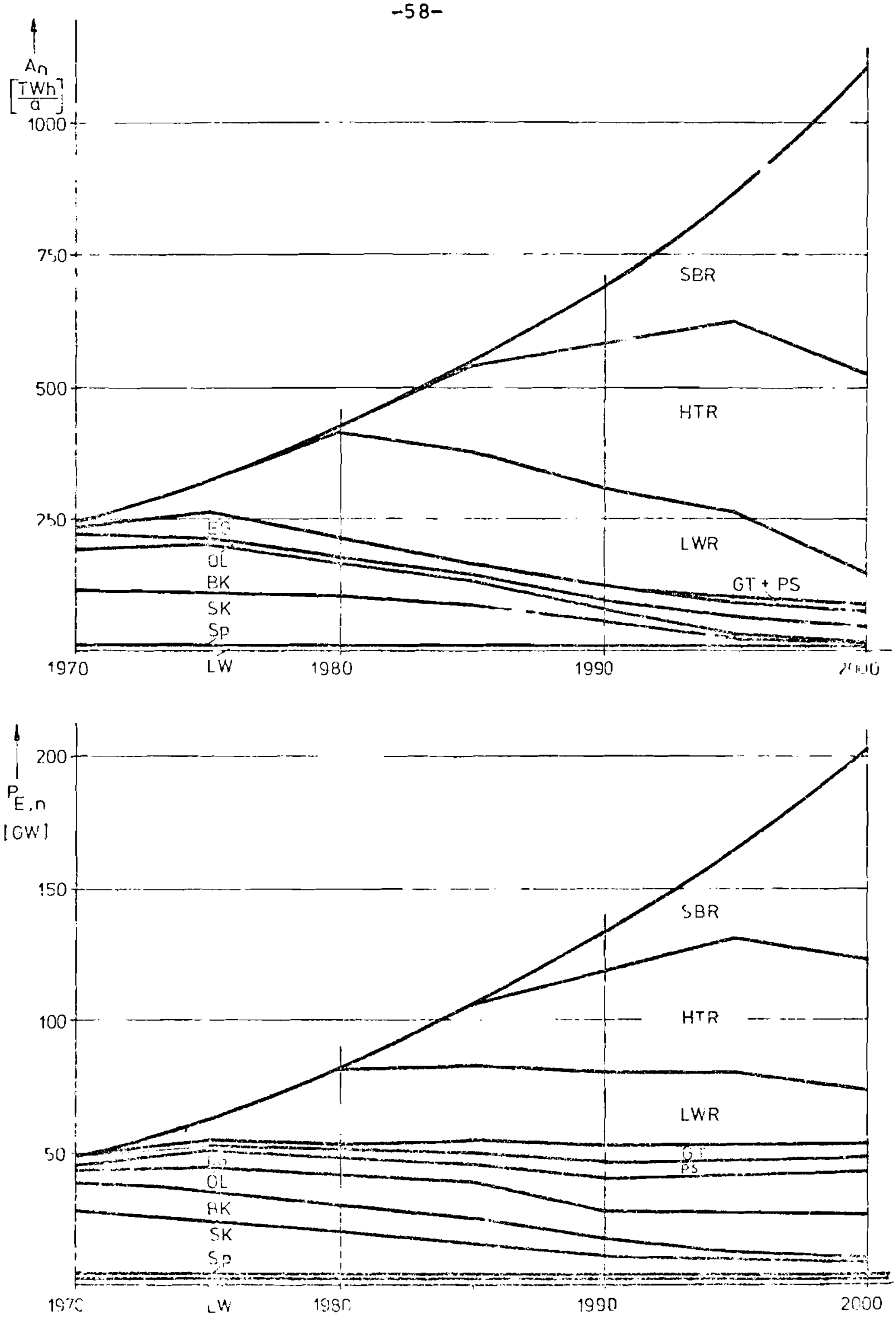


Fig.6: Example 2: Nonlinear Programming

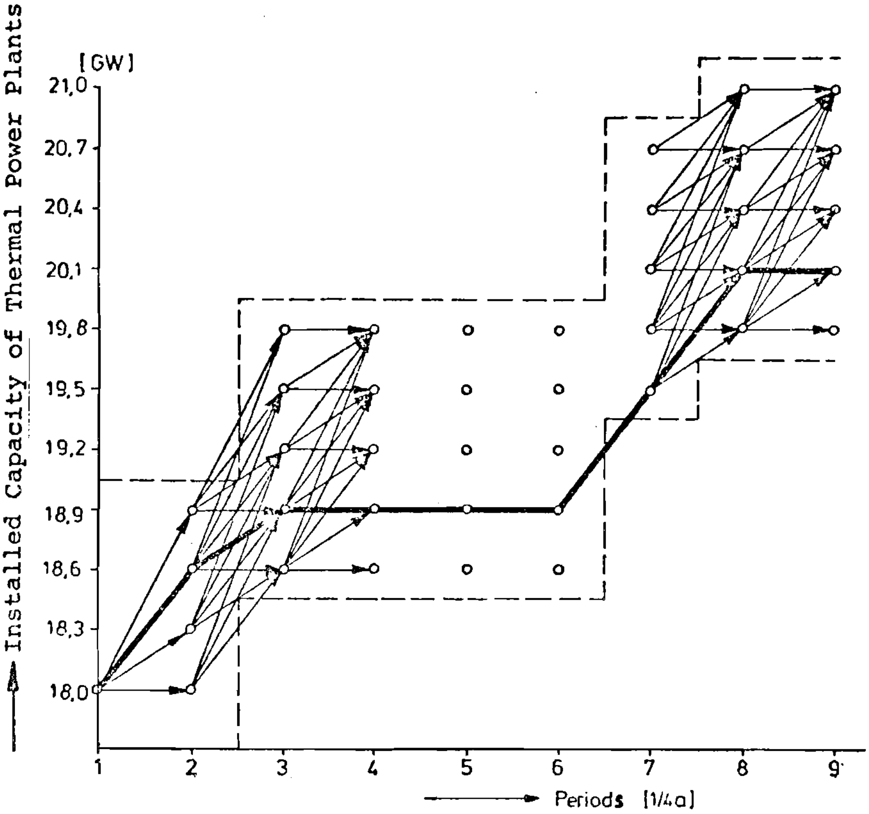


Fig.7: Illustration of DP to Install Optimal New Power Blocks

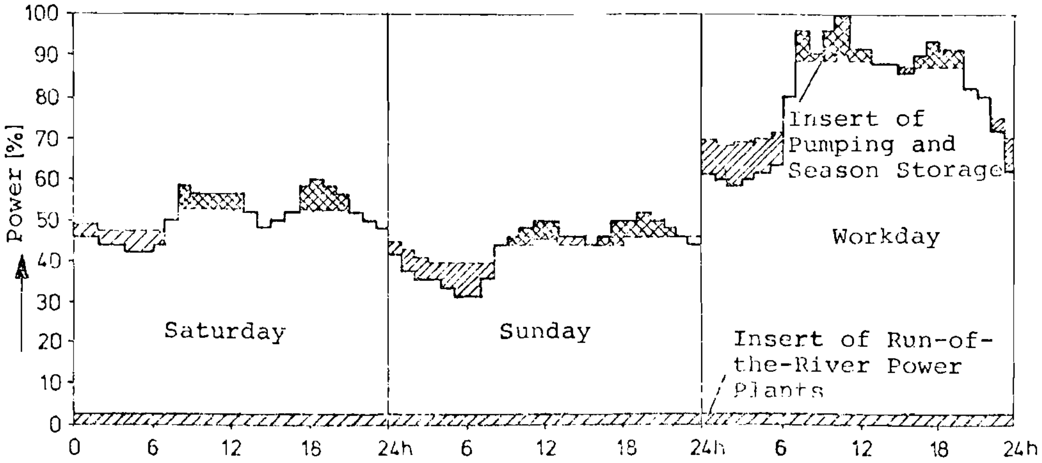
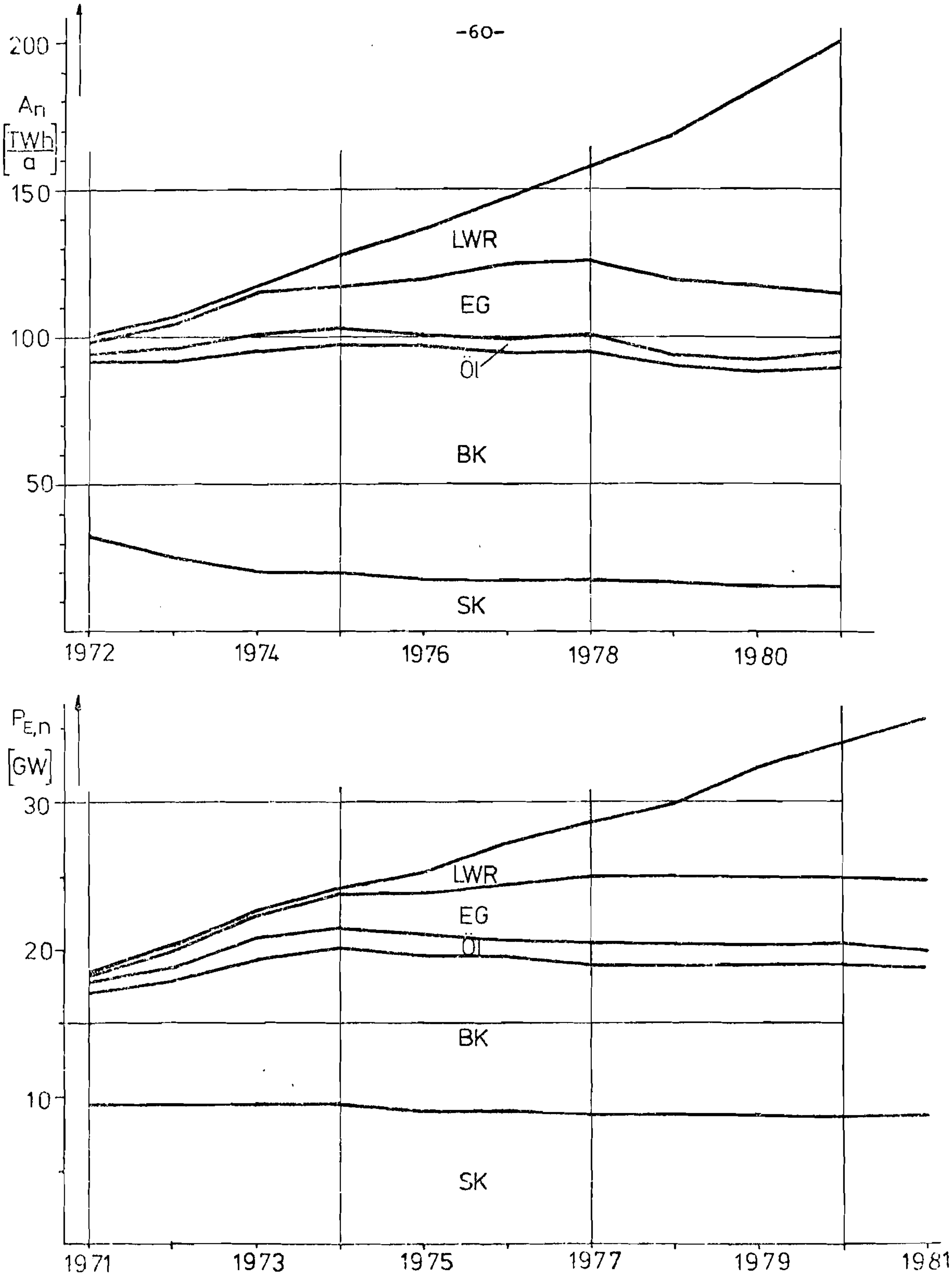


Fig.8: Characteristic Daily Generating Diagrams of a Quarter of a Year, Normalized with its Maximum Demand



<u>Fig.9</u>: Example 3: Dynamic Programming

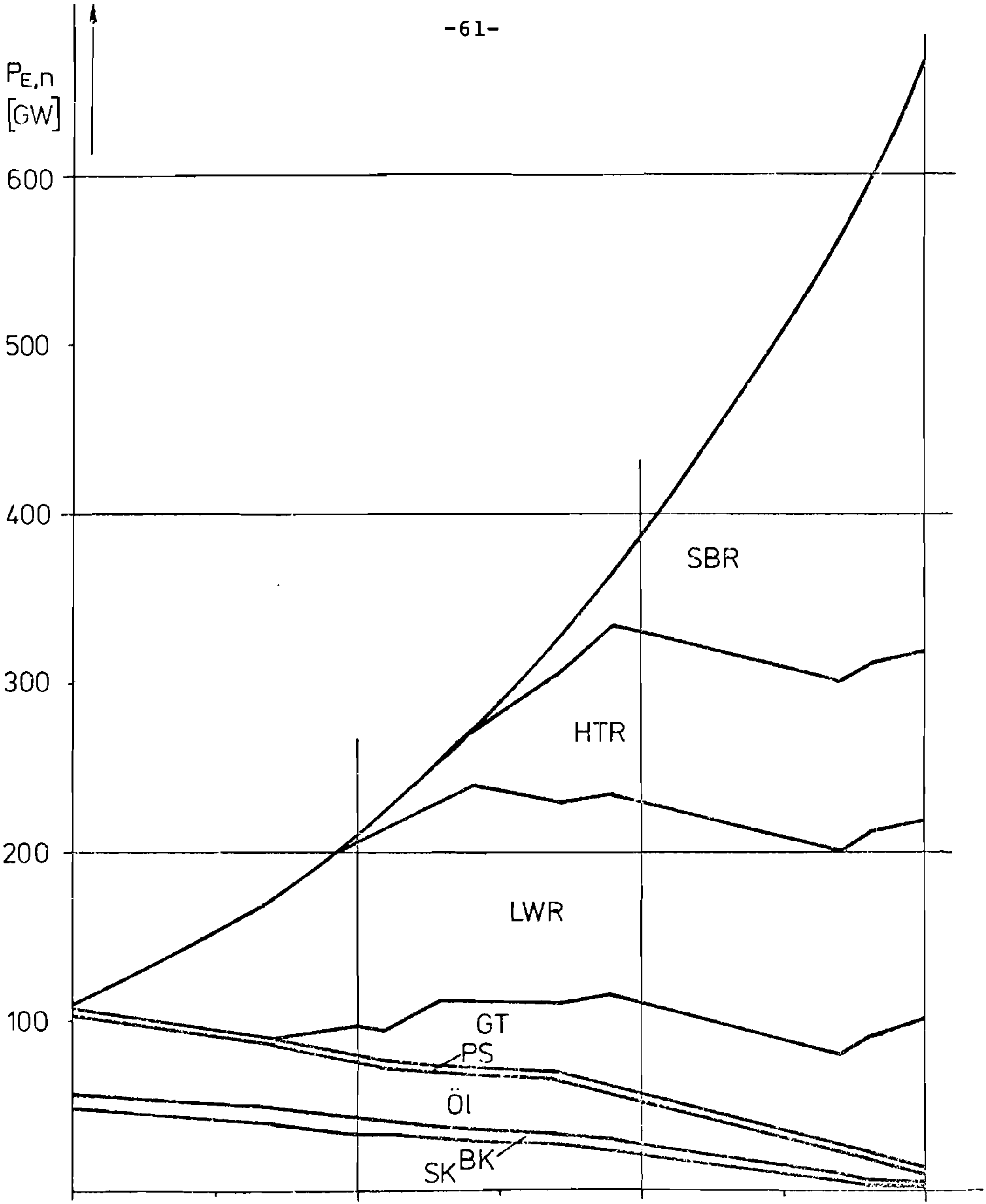


Fig.10: Comparison 1: With LP calculated distribution of Power

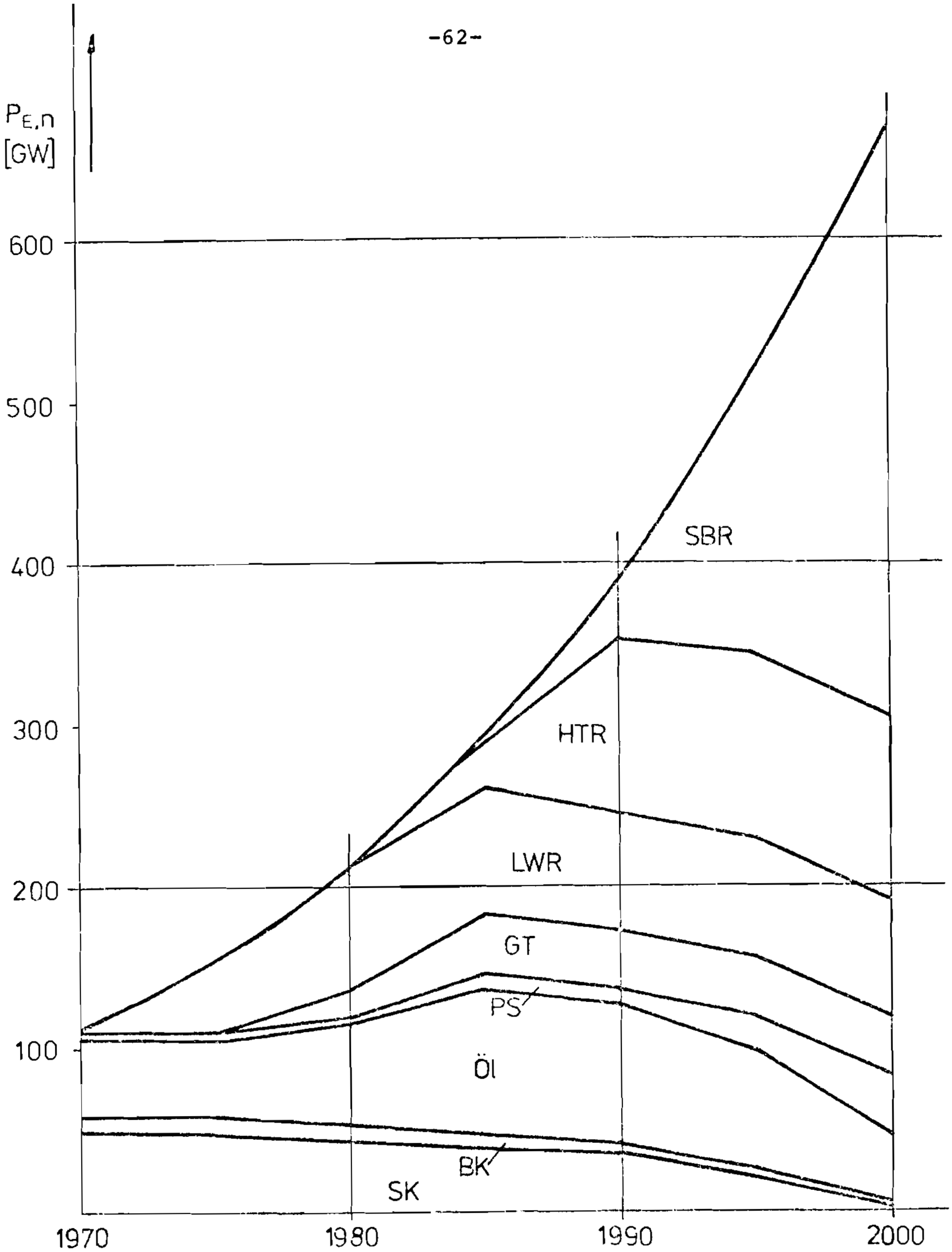


Fig.11: Comparison 1: With NLP calculated distribution of Power

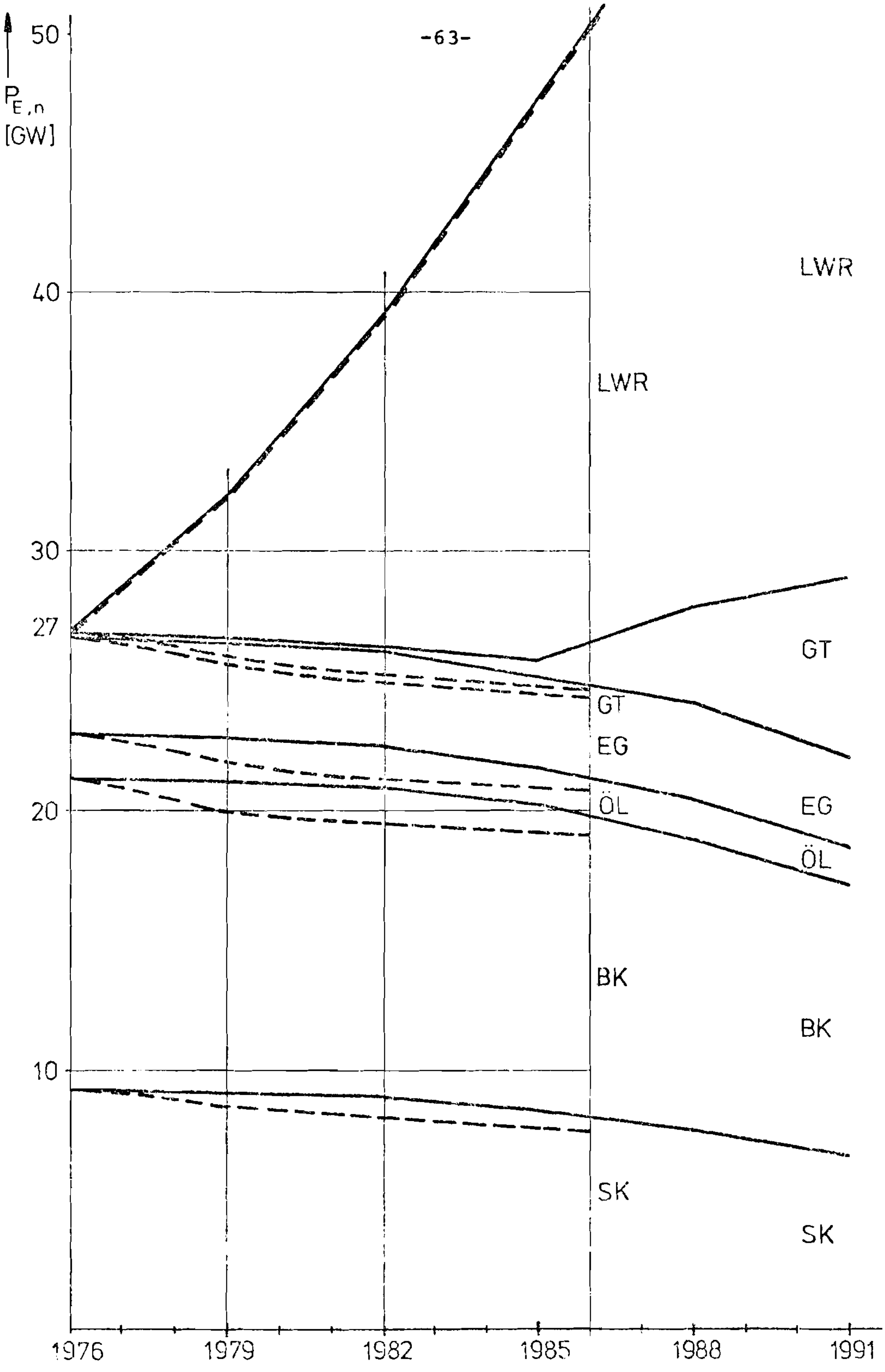
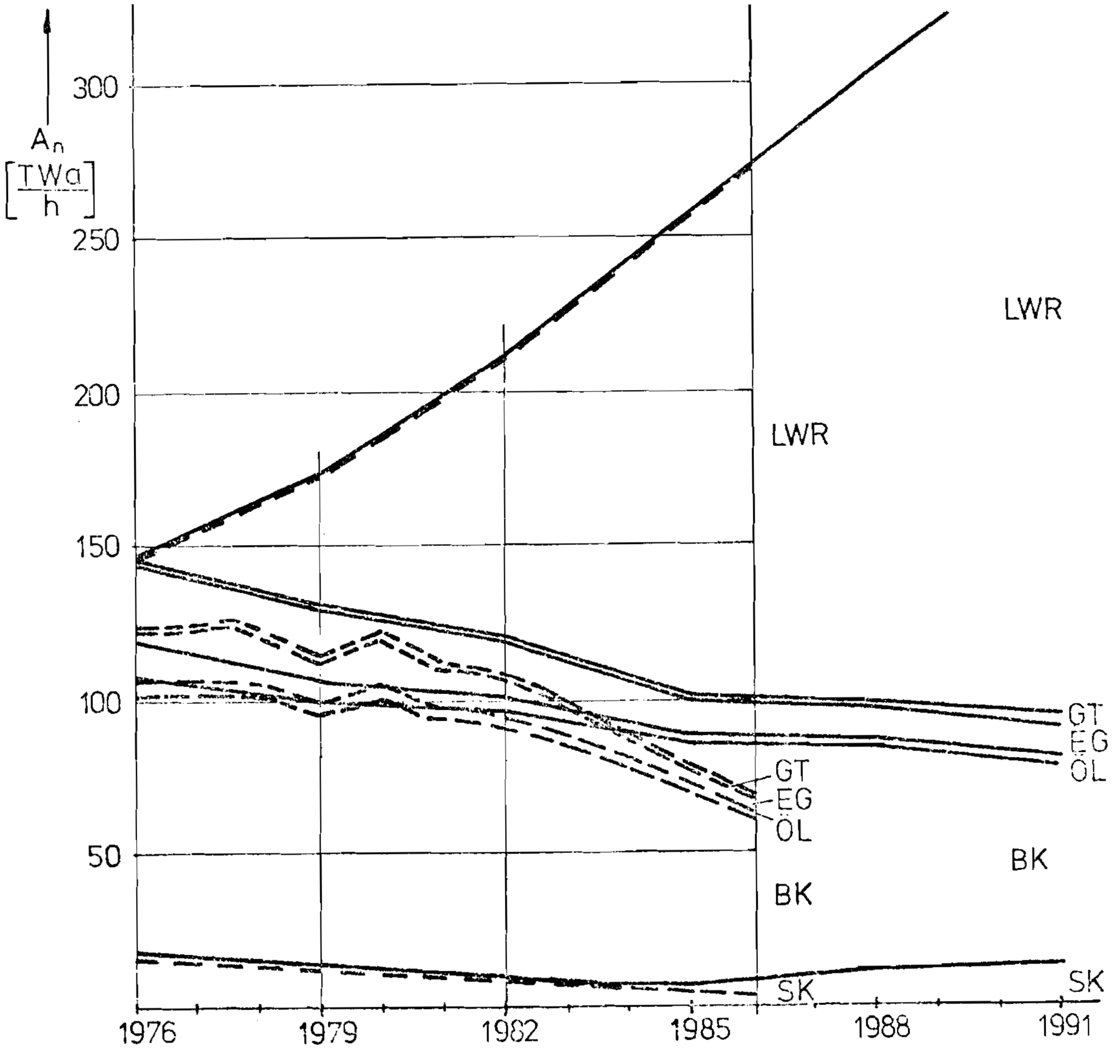


Fig.12: Comparison 2: Distribution of Power

—— NLP ----DP



<u>Fig.13</u>: Comparison 2: Distribution of Energy

—— NLP ----DP

T a b l e 1

optimization method	example	planning horizon	number of variables	core storage required	execution time
LP	FRG 9PPT	35a	70	26K	67s
NLP	FRG 10PPT	30a	109	29,5K	900÷1400s → exactness increasing
DP	NRW of FRG 133PP	10a	(40 periods to 6 points each)	new instal.30,5K insert 38 K	 210s 600s

Legend:

PP = power plant
PPT = power plant type
NRW = North-Rhine-Westfalia
FRG = BRD = Federal Republic of Germany

Table 2	Characteristics		
model / criterion	LP	NLP	DP
planning area	unlimited	unlimited	limited by number of power plants
planning horizon	>15a	>15a	~5 ÷ 15a
planning step	year	period (e.g. 5a)	period (e.g. $^1/_4$a)
plant installation	continuous, in types	continuous, in types	discrete, in blocks
consideration of the pumping-storage station	→	→ increasing	→ as one type
restriction of the energy production	simple to consider	simple to consider	difficult to consider
restriction of the power generation	''	''	simple to consider (e.g. declaration of one plant installation sequence)
image of the energy consumption	annual generation duration diagram (GDD) (rectangular)	annual GDD (trapezium)	daily GDD
costs	for types, function of time	for types, function of time	for blocks distinquishing of each block of the type), function of time
number of variables	some 1000	<~150	installed ~15 existing ~150
kind of optimization	stepwise	integral	stepwise
exactness of the system representation	→	→ increasing	→
core storage required	→	→ increasing	→
execution time	increasing →	→	

Discussion

The participant who opened the discussion asked how they consider the shut down periods of the different plants. Mr. Modemann replied that this is done by a reserve capacity which in this study comes up as 11 to 12%; details of the calculation are given in Ref. [5] of his paper.

Another delegate then asked if social and environmental costs had been considered in the model. Mr. Modemann replied that they had not, but noted that they will do this in a new study which has to be done for the Ministry of Research. Then this delegate claimed that the results will change tremendously because, for example, the storage cost of plutonium for more than 1,000 years is infinitely high. One way to manage this problem is to reduce the energy demand.

Mr. Janin (France) then made two comments: First, he remarked that they are studying many of these kinds of models. They found that the crucial point with these models using linear programming is to get the energy storage problem properly programmed in. Now they use control theory which seems to be much more efficient. Finally, he asked whether these models are used to get a very precise forecasting of the plant capacity which has to be installed in the near future, or to find out the extension of nuclear power stations in the future. Mr. Modemann replied that these first studies have been done to forecast the nuclear power plant installations. But, as he noted, the nonlinear programming model is used for the long run and the dynamic programming model for the short and medium run.

A Study of Infrastructural Impact on Long Range Energy Transports

Acad. Styrikovich

The problem of long range energy transport is a very complicated one. It is closely related to the development of infrastructure, especially when energy resources are transported from less populated regions or when they are transported through regions with the least developed infrastructure. Such problems exist in the USSR, as well as in other industrialized countries developing natural resources in new regions. For this reason, the USSR is carrying out intensive research and development connected with infrastructural impact on long range energy transportation. Up to now only some problems were evaluated in these investigations, and therefore the method of concrete designing was used. As a result, it is not possible to relate the complete studies of this problem using systems analysis; at present, only information concerning concrete investigations of this problem is available.

Because the conditions of infrastructural impact on long range energy transportation are typical (not only for the USSR but also for other countries which are exploring or trying to explore energy resources in new areas), I hope that this topic will be of interest to all participants.

In the USSR, the problem of long range energy transportation in the form of electricity, as well as fossil fuels, is especially important. The bulk of industry and about 75% of the population are concentrated in the European part of the USSR, including the Ural industrial area which is located at a distance of 2,000 to 4,000 km from the biggest deposits of cheap fuels and abundant hydro-resources in Siberia. Drastic measures to speed up the economic development of Siberia with the construction of big energy consuming industries have helped to increase energy consumption in the East; however, a shortage of energy resources in the European part of the USSR remains, and the deficit grows rapidly. Therefore we face the complex and challenging problem of transferring huge quantities of fuel and electric energy from East to West. In the first place, this involved north-western Siberian oil and gas which can be extracted economically on a very large scale. The transport of oil is not as big a problem, since the oil fields are concentrated in rather small areas from which we already have two oilpipes, 100 and 120 cm in diameter. The second pipe has a capacity of over 100 million tons per year. The transportation costs of these big pipes normally do not add too much to the price of oil, even at distances of up to 3-4,000 km. But this region was initially an unpopulated swamp and forest, with almost no existing infrastructure. For the transportation of all equipment needed by people as well as oil production, the big river Ob was used; but due to the climate navigation on this river is only possible in the summer (a very short season).

The difficulties grew with expansion of oil production, adding still another problem. The amount of gases released by oil also grew with oil production. In the beginning these were burned on the production site, but this burning of such large quantities was later proven to be an uneconomical method, and thus the decision was made to build the costly, though necessary, railroad to transport liquid gas and all other goods. Last year, when the oil production in this area reached approximately 100 million tons, the first line of this railroad was completed between Tobolsk and a new town, Surgut. In the near future, this line will continue to Nizhnewartowsk, on the bank of the Ob river. (The present population of each of these towns is around 50,000 people.) Several plants for gas processing are now under construction, each plant producing a different product. Dry gas and methane will be transported to a large thermal power station in Surgut. The capacity of this plant is over 1,000 MW today and it will be doubled in the coming year. Propane and butane in liquid state will be transported under elevated pressure by railroad to petrochemical plants. Because 80% of this area is swampland, transportation of equipment from the banks of the river is possible only in the second half of the winter when the swamps are frozen.

Today we have a permanent route by rail to the biggest oil fields and town, Surgut. In addition, we have an increasing though expensive (due to the construction over swamps) network of paved roads for auto transport. The entire region is also covered by an electrical grid connected with the Ural energy system by a 500 kV line. This was initially constructed to supply the oil field areas, but now the surplus of electricity from Surgut's power station goes back to the electrical system of the Ural. Today, however, there is some development of infrastructure in this region.

Other conditions are still in existence in gas fields located approximately 600 to 1,000 km to the north. Proven resources of dry gas in this region near the Polar sea are large, but there exists almost no infrastructure. Transportation of all equipment and goods is possible only in a very complicated manner:

1. by ships via the Polar sea, which can be passed only in the latter part of the summer;

2. by small rivers up stream--only in the following spring, at high water; and
3. only in the second half of the winter through frozen swamps, which added together makes almost two years total transport time.

During any other time of the year, transportation is only possible by using helicopters, a very costly method. Under these present conditions, new constructions are limited to the minimum needed for gas production and transport. Only a small number of completed towns, generally located near the sea shore, grow rapidly. There exists a large pipeline from one of these towns to the gas network, and others are under construction. Explorations of other gasfields are carried out mainly on an expedition basis--only workers and a small number of assistants for service are living in limited new houses and trailers specially designed for the extremely cold climate. One team works in a very small village in the far North for two weeks at a time; then they are transported to their families who prefer living in larger towns. While a second team moves into the remote village, the first continues working in the large town. With the rapid increase of gas production it will be necessary to improve the transport system to accelerate the progress of construction of pipelines, compressor stations, etc. Big questions have arisen in connection with the transport of natural gas itself, which is about six to seven times more expensive than oil.

Development work is now in progress in the USSR to make gas transport more efficient. We are already using 140 cm diameter pipes with maximal pressure at about 75 atm and such a pipe can carry $(30\text{-}35)10^9$ standard m^3/year. Even with this annual figure, the price of gas must be very significantly increased for distances of 3,000 to 4,000 km. Proven resources of natural gas in north-western Siberia are very large, about 14.10^{12} m^3, and the future annual output could be as high as $(500\text{-}600)10^3$ m^3; this output would require 15-20 new pipelines, but natural conditions (swamp, permanent frost, and almost no infrastructure at the present time), at least in the first 600 to 1,000 km of the route, make construction very difficult. Investigations on developing new methods of natural gas transport are now in progress, and should be considered as future possibilities. These might include the use of bigger pipes or the liquefaction or methane near the gasfields, followed by the transportation of this liquid gas in pipes under pressure at temperatures as low as -110 to -120°C. In the Case of liquid gas transportation, the number of pipelines will be reduced by several times. However, introducing such a method needs extensive research and development and huge capital investments in production of new equipment. The cost of such research and development is difficult to calculate in advance, and a limited number of such super-pipelines produce some difficulties in using linear mathematical models for optimization of all new transport systems.

Another example of the problems of connections between long range energy transportation and infrastructure concerns the explorations of the Kansk-Achinsk area in central Siberia, where huge deposits of exceptionally cheap brown coal have been found. It would be possible in the future to increase the mining of coal there to one billion tons annually under favorable conditions: open-cut mines with deposits reaching depths of 30 to 60 and even 100 meters. The capacity of each mine could yield 40 to 60 million tons per year, and the ratio of removed earth to coal is 2-3 m^3/ton. Under these conditions the price of coal at the site will be very low, 1 to 2 roubles per ton of raw coal or, at low calorific value in the range of 3040 to 3820 kcal/kg, about 2.5 to 3.5 roubles/ton of reference fuel (HCE). With such low prices of coal at this site and particularly cheap hydroenergy resources in the same area, Central Siberia is a zone well suited for the development of large industries with high rates of power consumption (for the production of Al, Mg, Ti, etc.).

Apart from local consumption of this coal, it is necessary to transport energy to the European part of the USSR. Basically, there are two solutions to this problem, both of which are presently being studied. The first is to increase the calorific value of coal (by converting it to semi-coke and mixing fine particles of this product with tar) up to 6500 kcal/kg and to transport this fuel by railways or pipelines. The second is to generate electricity at the mine and then transmit it to the West. Both ideas need extensive research and development before being put into practice on a large scale basis.

A new method of semi-coke production has been established today in a pilot plant only. An experimental industrial installation with an annual capacity of one million tons of raw coal is under construction. Within this project are several big installations with 30 to 50 million tons/year capacity. It is necessary to develop HVDC* lines for 1500 to 2200 kV for the transportation of electrical energy, since the 750 kV AC lines used today would be an uneconomical solution. Intense research and development in this field gives us reason to believe that the first power line of the new type may be in operation in the early 1980's. In the problem of utilization of this Kansk-Achinsk brown coal, we have quite a different set of connnections with infrastructure from those for the oil and gas of north-western Siberia. Deposits of this coal are located near the great trans-Siberian railroad and only short supplementary roads must be added.

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*HVDC: high voltage direct current.

Of course, the organization of such enterprises at a production level of several hundred million tons of coal annually (including the extremely high productivity of each worker), as well as the construction of 14 to 16 electric power stations, each with a capacity of over 6,000 MW, means creating an extensive new industrial region. The transportation line itself will not produce too great an impact on the rather developed infrastructure of the long route. The line is specially connected with the EHVDC* lines which will only carry electricity from the initial to the final point, almost without connection with the electrical grid of the country being crossed by these lines.

The problem of raw coal or semi-coke transport is quite different. If it is to be transported by railroad, then it is necessary to take into account that such a way is a universal type of transport. There are difficulties in distributing all of the capital investments and expenses between the main bulk of coal for transportation, for which this railroad is designed, and the other users, because the latter gain additional benefit from new railroads.

If the means of transport is to be a pipeline for a coal-water slurry mixture, or for coal transportation in containers, this specialized type of transport adds little to the infrastructure of the country crossed by such a pipeline. Also, in this case it will be possible to supply the users with semi-coke at some point along the pipeline, and not only at the final point as in the case of the EHVDC line.

Under such conditions, long range transportation of electricity and fossil fuels is, for the USSR, a substantial part of the entire energy complex, and must be included in the system of models used for the optimization of the complex future development. In the first stage of investigation, optimal rates of production of electricity, heat energy, and all other types of fuel must be established, as well as distribution rates of production between the biggest coal, gas, and oil fields; optimal rates of construction of thermal, nuclear, and hydrostations must also be investigated. The result of this work is the optimal development of the energy complex for the USSR and for each big economic area.

For such work we use, as a rule, several types of linear mathematical models. These models include expenses for production, transport, and utilization of different energy resources, and the optimization of distribution of each type of resource between consumer groups and economic areas. As a result we have the so-called "closing expense" or "price of op-

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*EHVDC: extremely high voltage direct current.

timal planning" for each type of fuel in a number of economic regions.

Because of the long range of transport, these prices change very significantly in the various parts of the USSR. They are very low in Central Siberia, and very high at the western borders of the USSR. For example, the price of coal will be 2.5 to 3.5 roubles/ton in Central Siberian power plants, and 20 to 28 roubles/ton at the western border.

Discussion

One delegate asked whether iron can also be found in the region where there is plenty of coal. Mr. Styrikovich said that they have iron in the central European part of the USSR. Therefore, they have a transportation problem because a large amount of coke is required; up to now transportation has been by rail.

Another participant made the comment that in the USA there is increasing concern over the burning of coal, particularly in populated areas, because much of it is high sulphur. Furthermore he inquired if they had included in this analysis the shipping of coal to the European part of the USSR, and the effects of environmental problems associated with coal burning there. Mr. Styrikovich replied in the affirmative and remarked that coal has very low sulphur content and that the large power stations will not be situated near towns. Therefore, they have some proof that the standards will not be exceeded if high chimneys are used--and the highest chimney today is 320 m.

Mr. Raiffa then noted that he had been fascinated by the presentation and that he hoped that some of the presentation could be followed up with research effort at IIASA, as they are concerned with many of these problems. Further, he remarked that in October they plan to start a series of conferences on major integrated planning efforts. He mentioned that he had spoken to Prof. Gvishiani and Prof. Ananichev about the problems, and that they decided the first of this series would handle a problem in the USA; the problem with which they hope to deal will be inter-urban planning of the Tennessee Valley Authority, called TVA. Then he pointed out that they had further decided that future conferences should be devoted to problems of very complicated systems planning efforts in the development of the Siberian region. Mr. Raiffa then came back to the problems with the gas and oil fields that Mr. Styrikovich had raised, and remarked that it would be an ideal subject for such an international conference, because many of the systems problems they are facing in the USSR have counterparts in the north-west region of many other countries as well. Mr. Styrikovich replied that it would be very helpful to study the problems of these remote areas. Then Mr. Raiffa mentioned that they decided to feature problems of national settlement policies and problems of developing the infrastructure of remote areas. Finally he noted that this is a theme which is running through many of their projects and would, therefore, be a good case study.

Mr. Häfele had a question about the exploitation of the large energy resources in the USSR. He asked what the planning horizon is in order to get that kind of energy transportation on a large scale. Mr. Styrikovich replied that the planning horizon is 17 years which means they will be planning until the year 1990.

Mr. Lopez-Polo (UNO) asked whether he had understood correctly that there is a direct current line with 1500 kV under construction. Mr. Styrikovich said there is and remarked that the first line of this planned superline is a direct current line with 1500 kV. There is no problem with high voltage as there are lines for alternating current with 750 kV, and these are working out very well in many countries. He mentioned further the necessity to get a new direct current line with 2400 kV in order to manage the large distances in the future, and this brings up insulation problems and environmental problems as well, which are now being investigated. Finally, he noted that there are also some projects of underground superconductivity cables for dense population areas and for rather short distances in the beginning.

Strategies for a Transition from Fossil to Nuclear Fuels

Wolf Häfele and Alan S. Manne

The paper "Strategies for a Transition from Fossil to Nuclear Fuels" is not reproduced here, but is available as a separate document from the International Institute for Applied Systems Analysis. Its publication listing is: RR-74-7, June 1974.

Discussion

One participant had three questions: (1) why only three types of reactors are considered in the model; (2) whether a construction constraint is used for nuclear power plants; (3) whether the prices of different fuels are treated as constant in the model. Mr. Häfele offered to answer the first two questions. The answer to the first one was that there are many possibilities in combining reactors with a nuclear fuel economy. But, as he stressed, with that model they wanted to study the transition from a fossil to a nuclear fuel economy for a typical case. Therefore, they used these three types of reactors in order to give one typical example for a nuclear fuel economy supplying electricity on the one hand and thermal energy on the other hand. The answer to the second question was that they did use a construction capacity constraint at the very beginning but that the construction capacity is now one of the results. Then he reported one of the results they have obtained with the model. He noted that if one has a reactor with a high breeding rate, then the construction capacity for various reactor types comes up to be smooth, while in the case of low breeding rate the construction capacity for the LWR turns out to be highly peaked. Then Mr. Manne responded to the third question; at first he remarked that there is no simple answer to that question. He noted further that constant prices in the sense of 1974 dollars are something like a GNP deflator if countries are going to inflate every year. So he pointed out that the concept, rather than prices, is first of all an inflation corrector. Furthermore, he talked about changes in relative prices. He noted that the oil and gas cost of $10 per barrel is exogenous. But there is a limited amount available. Therefore, the scarcity value of oil and gas that rises with time is treated endogenously. Now the rise with time is not nearly as dramatic in that case as the scarcity value of plutonium. So plutonium is endogenously priced. The scarcity value of oil and gas is also endogenous, but it is obviously influenced by how much one assumes to be available. If one assumes that infinite amounts are available, then it is clear that the price would be $10 per barrel for perpetuity, but if a finite amount is available, then it has a somewhat rising price.

Mr. Styrikovich (USSR) came back to the question of thermal energy supply and remarked that in a chemical industry in the FRG there is one LWR in construction which is proposed for the supply of electricity and process heat. Mr. Häfele replied that the LWR indeed can also be used for supplying thermal energy at low temperature, which is particularly used for heating purposes; but thermal energy transport can only be done properly for short distances. Further, he noted that the idea of this model is to use nuclear process heat as endothermic chemical reaction heat. So one has to transport energy in a chemical form and this can be done essentially independently of the distance. In this case the energy transportation problem becomes an ordinary transportation problem.

Another delegate remarked that there is a very great incentive for the model society to develop the HTGR type of process which could lead to synthetic fuels. Then he asked whether the large amount of coal in the USA makes it rational that the US government budget does not include any money for that sort of process.

Mr. Häfele replied that it is important to make a distinction between the supply of coal on the one hand and the supply of oil and gas on the other hand. He noted that only the supply of oil and gas is considered in the model. Further, regarding the reserves of coal, oil and gas, he remarked that one can say that hydrogen technology has to be used much sooner in Europe than in the USA, and that the model is representing a situation similar to that of Europe. Then Mr. Manne added that, in addition to the obvious discrepancy between the USA and the European situation on coal, it should be recognized that a lot of difference in the viewpoint related to the difference in the planning horizons. He remarked that if one only has his eyes fixed on the next 10 or 15 years, as in the "operation independence" project, then one does not look beyond. Therefore, in this case the best thing, of course, is to pump out all the oil and gas as fast as one can. But this is perhaps very short-sighted, and the whole "operation independence" project is probably a very short-sighted way of enabling one country to get out of its energy problems quickly. Furthermore, he noted that if one looks at a somewhat wider range horizon, then one might come to a slightly different conclusion than the emphasis on coal even in the USA. Then he stressed that, in other words, the model is considering the nuclear options versus the fossil options and that one is considering the hazards of a very dirty technology such as coal and shale--shale is probably dirtier than coal--versus one that has radioactive release problems. This means that the model has to find the best solution between something like billions of tons of particles or hundreds of tons of plutonium. Thus, he finally remarked that the problem is a choice between lesser evils.

WORLD ENERGY SUPPLY ANALYSIS

R. J. Deam

(1) SUMMARY

In September 1972 an Energy Research Unit[ø] was set up at Queen Mary College, University of London, to construct a World Energy Model. A model incorporating the petroleum and natural gas sector has been formulated in linear programming form, comprising some 4000 rows and 16000 columns. This has been experimented with in many ways to study, amongst other factors, the effect of a possible policy change, not only on the Sovereign State making it but the rest of the world. This paper, as a demonstration, illustrates one such policy change - the effects world-wide if we assume up to 30% of the natural gas demand in the USA was replaced by naphtha, No 2 furnace fuel oil or Low Sulphur fuel oil. We are not concerned how this may be brought about, e.g. by pricing legislation, but only with the effects.

(2) THE MODEL

(a) Basic concepts and objectives

The Unit set itself up with the following explanation and charter:

"It has been well established that an oil company system can be reduced to linear programming form which, when solved to optimise some economic criterion pertinent to the circumstances, leads to practical meaningful results. The system is one of economics, the logistics being bounded by sets of constraints not only physical but also social and political in nature. The World energy system is similar to the company system, except that the former is more heavily bounded by political and social constraints; the repeated attempts of national governments to formulate energy policies are at the same time confirmation of the heavy political and social overtones and of the need for some improved framework for decision-making if real crisis is to be averted.

[ø] Its members are: Prof R J Deam, Dr M A Laughton, J G Hale J R Isaac, J Leather, F M O'Carroll, P C Ward, S P Lumby and P L Watson

It is our belief that World energy is a social/political/economic system, which can be formulated in linear programming form, and hence solved, to give all policy-makers a valid common framework. Thus, through knowledge, better policies may be made, and major painful confrontations avoided.

The oil companies, like other energy suppliers, compete and trade within the given and future World system, which we believe is determined to a marked degree by political considerations. Oil, coal, and to a more limited extent gas are readily transported on a World scale; the national policy of one Country will affect supply/prices and hence competition in other Countries.

It is our belief that national energy policies can only be investigated within a world-wide framework, and that this is more, not less, true of the countries which import, consume and export large quantities of energy.

The linear programming systems used by oil companies have emerged slowly over the past two decades. The concepts and techniques built into such large, integrated systems cannot be described, nor their lessons learnt fully, without a great deal of time and some contact with the industry. The organisation of data, the computer routines, the methods of sensitivity analysis, the LP mathematics and so on, all are necessary parts of the whole, and each is a subject in its own right.

Here it is proposed to gloss over the mechanics and to suggest both the uses to which a World Energy Model may be put, and by inference, the reasons for its development.

Our demonstration model, incorporating 2 crude sources, 2 refineries and 3 markets, has been described elsewhere[ø]. This model shows how such an integrated oil company can be represented in linear programming form which may be solved for minimum cost. Within the system both refineries, although owned by the same Group, are competing for the same market which is allocated to each refinery on a minimum cost criterion. For example, the solution gives rise to the cost of each product at each refinery. If one adds the transport cost of each product from each refinery to each market, nowhere is it cheaper to depart from the optimal allocation. Given a perfectly competitive situation - with the allocation of the market to the cheapest source - the framing of the problem and solution would be identical were the refineries to be owned by different companies.

[ø] Reference 1 of present paper

The methods and philosophy applied to a single company are almost exactly applicable to the industry as a whole, subject to the assumption of perfect competition. Thus with the added reasonable assumption that competing forms of energy can be described in linear programming form, the great bulk of our knowledge and experience is applicable to a World Energy Model.

It is not intended to extend the time-horizon of the model, either in its static or multi-time period forms, beyond about 15 years. It will thus be able to take account of innovations in the employment of resources by existing technology, but not of the possible emergence of new technology. On the basis of our previous experience of planning models we believe that a time-horizon of this order is sufficient to enable the currently necessary decisions to be placed in their temporal context, and that little is to be gained by attempting to foreshadow the decisions of several decades hence.

Political constraints whether legal or fiscal (e.g. fuel oil tax) create a restricted environment within which perfect competition is assumed in our proposed models. An important feature of the model is that it will evaluate these barriers to competition. It is likely that a political constraint imposed by one nation will increase the cost of energy to other nations. For example, the social desire for a low sulphur in fuel oil in New York could have a marked upward effect on fuel oil prices in Europe.

The entrepreneur will no doubt use World energy models to determine his optimum market share and to reveal where prices are significantly departing from the perfect competition or equilibrium condition. The energy models on solution will give rise to equilibrium prices as a matter of routine. Where actual or predicted prices significantly differ from equilibrium ones, opportunity exists to prosper by helping to restore equilibrium.

It is of vital interest to measure the effect of changing the charges levied by the Organisation of Petroleum Exporting Countries (OPEC), and to determine the extent to which these charges may rise before painful confrontation occurs. The model could investigate the numerous aspects of this problem. Perhaps the most important use of a World energy model is to attempt to ensure the smooth supply of future energy at reasonable cost. Careful prediction of the nature and timing of fuel substitutions could save much wealth. The damage that could be caused by precipitous or ill-considered national policies to this smooth future supply would affect us all and needs expouncing.

The assumption of perfect competition, perfect knowledge of competitors' reactions, plans, etc., is idealistic. The goodness of fit will indicate the competitiveness of the industry and also highlight those areas where deviation is large. These latter areas could be subjected to physical (e.g. installation of new processing plant) and/or political intervention with advantage.

Enough has been said to indicate that the need for a World energy model exists, that most of the methodology and philosophy underlying the project are well known, and some possible uses have been indicated; the major problem is now one of assembling world-wide energy and economic data and not the least vital is a clear statement of political constraints imposed on the energy system. Experiments with the model and analysis of its solutions will soon identify those variables and constraints of importance and hence concentrate the mind."

Since then a model of the world petroleum and natural gas sector has been built and many runs made.

(b) <u>Brief description</u>

The model considers the world as 25 discrete geographical areas (Canada 2, USA 3, France 1, Scandinavia 2, and so on), 22 of which are also refining centres. The remaining 3 relate to Soviet bloc participation in the world scene with regard to exports of oil and gas.

52 different crude oils are represented in the model, the selection of these being based on the relative importance of crude types due to their location, quantity available, quality or political significance.

22 refining centres are considered. Available capacity in each area is based on the inherited situation, with future capacity being determined by the model to achieve the least cost satisfaction of area product demands. The processes considered, with their abbreviations are:

(1)	Crude oil distillation	CDU
(2)	Vacuum distillation	VDU
(3)	Catalytic cracking	CCU
(4)	Catalytic reforming	CRU
(5)	Alkylation	ALK
(6)	Kero and gas oil hydrocracking	H/C
(7)	Distillate (incl. GO) hydrofining	H/F
(8)	Residue desulphurisation	RDS
(9)	Residue coking	COK
(10)	Natural gas liquifaction	LNG
(11)	LNG re-gasification	Regas
(12)	SNG production	SNG

A comprehensive range of refined products can be produced in each area, each product being manufactured according to relevant specifications or restrictions.

The model is constructed so that the export crude oil represented can move to a wide range of possible refining areas in six size categories of ships (restricted by sizes of ports and harbours). The total fleet inherited can at a price be expanded by additions in each size category to achieve least cost satisfaction of product demand. Inter-area movements of refined products are allowed in three size categories; these can also be expanded at a price.

(c) Basic assumptions

The economic model makes three basic assumptions.

(1) It is shown elsewhere (refs 2, 3) that it is possible to construct equilibrium price equations between various forms of energy taking into account technology and economic factors; e.g. the price of regular motor gasoline could be equal to the price of naphtha plus the cost of reforming it.

The point to note is that, given the full technical model, equilibrium prices are indeterminate. The position is as if we had three unknowns but only two equations to determine them. For example, given the two equations:

$$x + y + z = 3$$
$$x - y - 2z = 1$$

we cannot determine the unknowns, x,y and z, because the equations can be satisfied by infinitely many sets of values. However, if the value of one of the unknowns is given, the other two can be determined.

Because the number of equations is only one less than the number of unknowns the indeterminacy is one-dimensional. Only a single external condition is needed in order to solve it. This one-dimensional indeterminacy is the situation found in energy models (and OPEC, the real world). This we accept at the outset since we must assume one external price, the price of light Arabian crude, to determine the equilibrium prices of all products, crudes and natural gas. Accordingly, these determined prices are not absolute, but, since we are interested in the effect on prices of a policy change, the resultant differentials, as will be shown later, are relatively insensitive to the assumed external price and hence are in practice realistic. Since we cannot determine absolute prices, but can determine changes in prices, we concentrate only on these differences.

Our basic assumption, reasonable when first made, but now outdated, is that the marginal crude, Arabian Light, is optionally available at $14.50/tonne, or $1.96/barrel FOB.

(2) Perfect knowledge and competition in the wholesale product, crude and natural gas market; this aspect is fully discussed elsewhere (refs 2,3).

(3) Energy demand is increasing and this assumption is not likely to be challenged as a long-term trend. This allows us to determine, not estimate, and in essence we take a future demand pattern and determine the least cost solution of meeting it. We leave it to the reader to decide when the stated demand will be reached.

The solution determines a host of factors: supply logistics, equilibrium prices, etc., that should prevail when the demand pattern is reached. Significantly, we determine the capital budget for new refinery plant, oil tankers and so on. Since the lead time for new plant etc. is in the order of 3 years, whether we are looking 5 or 7 years ahead is not significant, when making investment decisions. We do not stop to consider this important point as this is discussed in Reference 4.

(d) Basis of runs

In the preliminary runs we have taken the world situation, as at the end of 1972, as given, and taken a demand pattern for a period five years ahead in 1977. Whilst we accept the total demand pattern the split between products is allowed to vary within the model via economic substitutions. The one variant case we discuss later forcefully illustrates this point.

The current model has the following basis:

(1) A product demand pattern for 1977
(2) Existing 1972 refinery plant and tanker capacity
(3) Crude Productions for 1977
(4) Product specifications for 1977
(5) Yield data on crudes, blending indices, etc.
(6) Operating and capital costs of new refinery equipment by areas and also for tankers by size category, as seen in 1977
(7) Port and harbour constraints as seen in 1977
(8) Current political constraints as seen in 1977.

(e) Output information

The output from each run is very voluminous, amounting to some 600 pages of computer print out, or 8 lbs. of paper. Since it is impossible to report all the information (or for the reader, at first, to absorb it), we highlight some of the information in appended tables. As we are mindful of this American audience, we have chosen here to highlight the effects of a possible change in a USA political constraint - namely up to 30% of the natural gas demand can be substituted by liquid products (naphtha, No 2 furnace fuel oil, low sulphur fuel oil).

The value of models lies primarily in their ability to evaluate changes, not to estimate exact building programmes. The latter requires very exact information; the former, since errors tend to be self-cancelling if we measure differences, is less exacting.

(3) BASE CASE

(a) Refinery plant construction

Table 1 lists the new refinery plant capacities by area, in thousand B/SD, per the Model solution, that will be added by 1977. These are on top of existing capacities in the base year of 1972, with negative figures representing unused capacities already available in 1972. Row A indicates that in Australia all the inherited crude capacity is employed but it is not economic to build extra capacity, while there is a surplus of 249,000 B/SD of vacuum distillation capacity, which remains unused. The world-wide totals of new capacities are given near the bottom of the Table along the "Total Built" row, which gives 9,181,000 B/SD of new crude distillation capacity, 2,902,000 B/SD of new vacuum, and so on. The row below this entitled "Unused Capacity" shows the inherited capacity, at zero rent or cost, that is spare. For example, 1,837,000 B/SD vacuum distillation capacity remains unused even though 2,902,000 B/SD is built in other areas. The last row reports the net capacity usage world-wide, this being of value when analysing the results for some refinery processes.

These figures are very sensitive to the inherited position. For example, if the inherited crude unit capacity in UK and Eire was overstated by 100,000 B/SD, then not 453,000 B/SD but 553,000 B/SD would need to be commissioned. However, as we shall be concerned with differences when considering variants, this tends to be self-cancelling. We are aware that the surface is reasonably flat in our solution and, from other results, we know that with slightly different assumptions more platforming and less cracking takes place. However, both solutions give rise to very similar total capital and overall costs. Be this as it may, the building programme given is a reasonable guide to the world's refinery plant construction. The unused capacity is indicative of very premature building programmes in the past.

Table 2 summarises the refinery capacity totals on a world-wide basis for individual processes for both the base and variant cases.

(b) Tankship construction and operation

Table 3, a shipping comparison, summarises the main results of the computer solution, with the first column showing the results obtained for the base case on which we will concentrate for the moment. The first half of the table expresses equilibrium freight rates for the six size categories of vessels on the route from the Persian Gulf to Rotterdam in terms of Worldscale. We note that vessels of less than 25,000 dwt command an equilibrium spot freight of 97.3% of Worldscale, 25-50,000 dwt vessels a rate of 86.6%, reducing to a value of 60.4% for vessels of greater than 200,000 dwt capacity.

The second part of the table shows the total of new oil tankers to be constructed to meet the demand pattern of the base case by 1977 as 96.4 million deadweight tons. Of this total, 94.8 million deadweight tons are in the largest vessel size category of over 200,000 dwt capacity, and the remaining 1.6 million dwt tons are in the 125-200,000 dwt capacity range, while the inherited capacity after depletions in 1977 is sufficient to cover requirements for smaller sized vessels. The values shown in brackets in this part of the table are the penalties calculated by the model against building these smaller vessels, and these indicate that the owner of a 25,000 dwt vessel would fail to recoup his annual capital charge by some $67.3/deadweight tons/year, but penalties reduce with increasing vessel size, so that the owner of a vessel in the 80-125,000 dwt size category would lose only $5.8/dwt/year.

The results for the base case confirm the current paradox that the difference between the spot freights of smaller vessels and the larger ones do not reflect the cost differentials. Tankers have long lives and the smaller vessels have been over-constructed in the past, presumably because investment decisions were made on cost and not value judgements.

The LNG ships are built in the larger of the two sizes, 125,000 cu. meters. All of the existing capacity, of this size and the smaller 75,000 cu. meters, were fully utilized.

Finally, in Table 3, the deadweight tonnage employed in product movements, limited to the three smallest size categories, is listed. This type of trade was allowed for when determining the new tonnage requirements for 1977.

(c) Capital Expenditure

Table 4, first column, shows for the base case, the capital to be spent between the end of 1972 and the terminal year, 1977. Thus, for example, to build the required new refinery plant in Australia some $15 million would be spent (Table 1 shows this to consist of new catalytic reforming and alkylation capacity), while in the UK and Eire, $591 million would be spent, and so on. In total, the non-Communist world requirement for new refinery and LNG plants would cost $21.3 billion. On top of this, $12.6 billion are required for tankers and $6.5 billion for LNG carriers to reach a total of $40.4 billion in the refining and shipping sectors.

(d) Natural gas

Table 5 shows, for 19 different producing areas, the available gas supplies assumed for 1977 and, for the base case, the corresponding unused gas supplies and the equilibrium prices of the gases at the well-head. The gas quantities are quoted in units of million bbls/CD as fuel oil equivalents, and the equilibrium prices as $/Bbl FOE. With the gas prices being those at the well-head, then for LNG export schemes, the prices are not only before ocean freight in refrigerated tankers, but also before liquefication at export point and before pipelining from the field to the liquefication plant.

For the base case, of the 359,000 B/CD of gas (FOE) available in Australia, only about a half, 189,000 B/CD, is utilised, with the other 170,000 B/CD left alone. Brunei, on the other hand, lifts its entire availability of 359,000 B/CD and its equilibrium well-head price is $0.38 per bbl FOE. Of the gas production capacities thought to be available in 1977, those in Australia, Pakistan, Persian Gulf and Siberia are not utilised to the full. The prices tabled, and the utilised gas quantities, are relative to Arabian light crude at $1.96/bbl FOB.

(e) Equilibrium product prices on wholesale basis

Table 6 gives these prices, $ per bbl, for the base case, by area. For example, reading across the first row, equilibrium prices in Australia are: $2.92/bbl for Refinery gas and LPG, $3.48/bbl for Light distillate feedstock, and so on. In absolute values, these prices are very sensitive to the assumed price of $1.96/bbl for light Arabian crude. In our discussion we shall be concerned mainly with differences rather than absolute values, and these differences are relatively insensitive to crude prices, over reasonable ranges. This can be seen as follows:

A product price can be thought of as made up of two parts. One part arises from freight, capital and operating expenses, and the other is based on crude costs. For example, a product price of $4.0/bbl might be made up as follows:

Freight, capital and operating costs	1.65
1.2 x Price of marginal crude (1.96)	2.35
	4.00

with the factor of 1.2 implying that to make an extra barrel of this product, 1.2 bbls of crude oil are required.

In general, the relationship between a product price P_x and marginal crude price P_c is

$$P_x = a + bP_c.$$

If this refers to the base case, then in a variant it is replaced by

$$P'_x = a' + b'P_c.$$

Thus the change in product price in the variant is

$$\Delta P_x = P'_x - P_x = (a' - a) + (b' - b)P_c$$

where a'- a represents differences in freight, capital and operating charges between variant and base case, and b' -b is the change in the amount of crude oil needed to make a ton of product, usually a small differential.

It follows that the effect of changes in crude price on differences between product prices is of second order. If the assumed price of crude is changed from P_c to P'_c, the effect on a product price comparison is:

$$\Delta P'_x - \Delta P_x = (b' - b)(P'_c - P_c).$$

It consists of one first-order difference multiplied by another and is therefore of second order. This is why product price comparisons are insensitive to moderate changes in assumed crude oil prices.

(f) <u>U.S. supply and demand logistics</u>

Table 7 shows imports of crude oil and products into the three US areas, by tanker size, for the base case. Table 8 shows how a computer solution can be arranged to give comprehensive supply logistics for oil liquids covering a sub-continent, here portrayed as the base case results for the three US areas, but with the national supply figures summarising as:

	Million Bbls/CD	%
Domestic supplies (crude oil, natural gas liquids, etc)	11.04	50
Crude oil and NGL imports: From Canada	1.13	5
From other countries	4.61	21
Products	5.28	24
	22.16	100

Table 9 shows how natural gas demand could be met in the three US areas in 1977, with the LNG shipments from Southern Alaska to the West Coast net of amounts transferred by pipeline to the inland Central area. The gas supplies on a national basis total:

	Million Bbls per CD (FOE)	%
Domestic production (incl. Alaskan LNG)	11.26	69
Domestic SNG	1.21	7
Pipeline imports (Canada)	1.39	9
LNG imports	2.47	15
	16.33	100

(g) Equilibrium prices of crude oil

Table 10 indicates the quantities of crude oils available on a world-wide basis for the model in 1977, and the corresponding qualities. For example, the 820,000 B/CD of crude available in the UK sector of the North Sea is all classified as Forties crude, when considering crude qualities, and this has a 36.6 API gravity and a 0.28% wt sulphur content. The crude oil availabilities for different areas summarise as:

	Million Tonnes/Annum	'000 B/CD
USA	459.9	8,802
Canada	103.8	2,092
Latin America	174.0	3,266
North Sea	75.0	1,531
Africa	277.0	5,706
Middle East	2,070.0	40,876
Indonesia/Australia	115.0	2,378
	3,274.7	64,651

No North slope crude from Alaska is assumed available, while the relatively small amounts of crude produced in continental Europe, such as Germany and France, are assumed to be processed in local refineries and not available for export.

Table 11 gives the equilibrium prices at the fields for the crude oils. Thus in the column for the base case it will be seen that the Forties crude, taken as composite for the UK North Sea, has a field value of $3.13 per bbl the same as that in the adjacent Norwegian sector (Ekofisk crude), related to the $1.96/bbl price for Arabian light crude.

Besides Arabian light, four other Middle Eastern crudes were taken as marginal crudes, and for given f.o.b. values and permitted maximum production availabilities, the computer solutions indicated what crude liftings would be for each (see bottom of Table 11). The relevant data for the base case are:

	$/Bbl	'000 B/CD Max. Avail.	'000 B/CD Quantity per Solution
Arabian Light	1.96	20,270	18,630
Arabian Heavy	1.90	2,720	240
Kuwait Export	1,91	3,370	2,710
Iranian Light	1.99	5,040	3,290
Iranian Heavy	1.98	2,970	2,670

(4) THE VARIANT CASE

(a) General

Each computer run minimises the total cost of meeting the given demand pattern under specified conditions. The total cost that is to be minimised in our model consists of the following components, calculated on an annual basis:

(1) In relation to new capital assets (refinery plant, tankers, etc.) an annual charge representing 15% DCF over the estimated life of the asset, together with insurance, maintenance and (in the case of refineries only) manning and overheads.

(2) The running costs associated with the operation of both new and existing assets. For tankers these include crew, stores, port dues and bunkers, and, for refinery plant, chemicals and utilities (power and water).

(3) Payments for the amounts used of the five marginal crudes (representing mainly a monopoly rent paid to the exporting governments).

The total of these items is the functional in our optimisations, which, however, does not include the costs of non-marginal crudes, fixed charges on existing tankers or refinery plant, and possible savings by shutting down or scrapping existing assets, this last usually an insignificant item. The costs included in the functional are essentially those that can vary from one run to another. Thus, if we compare the functional values obtained for the variant with that of the base case, the difference represents the net effect of:

(1) A rise or fall in true resource costs.
(2) Changes in the amount of monopoly rent paid to owners of marginal crudes.

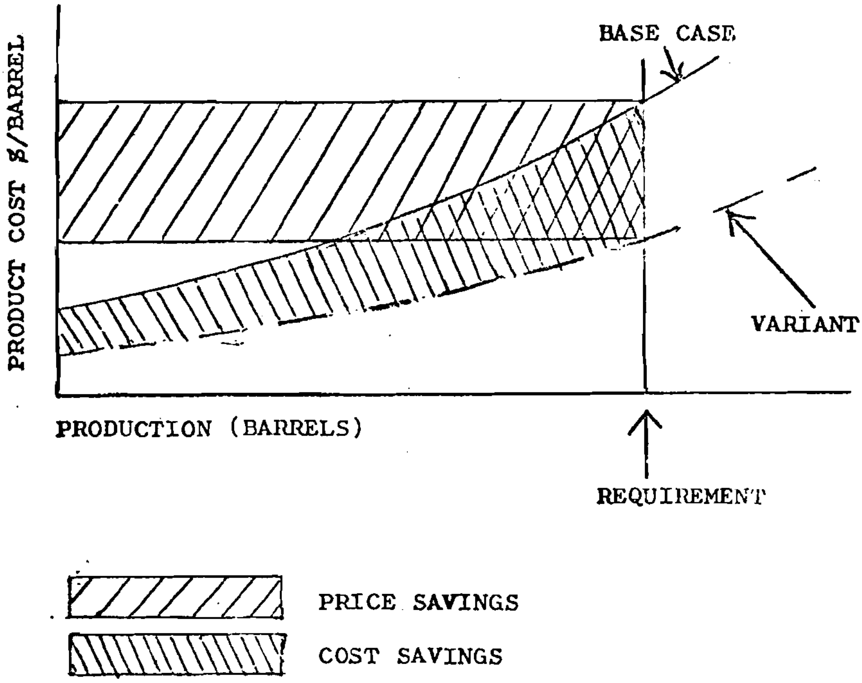
The minimised functional, as defined in this way, has been calculated for our two cases as:

$/Million/yr	Functional	Change
Base Case	45,324	-
Variant case	43,338	-1,986

Thus for our variant case where oil is allowed to be substituted for natural gas in the USA, the net effect of changes in resource use and of payments to the owners of the five marginal crudes in the Middle East is a saving of $1.99 billion per year.

Now this total cost saving does not equal the total consumer price saving. In fact it would be unusual if it did.

The diagram below explains this:



On this diagram, the solid curve represents the cost of successive increments in production in the base case, and the dashed curve shows corresponding cost elements in the variant case. In the case illustrated, the variant shows a saving over the base case. The amount of the saving is represented by the area between the two curves. This is the saving that shows up as a decrease in the optimised functional.

In assessing the saving to the consumer, we are concerned only with prices, not costs. Prices are, at competitive equilibrium, equal to the costs of the last increment in output. The aggregate payment by the consumer is therefore represented by the area under a horizontal line through the point representing this marginal cost. The saving to the consumer, or price saving, is the area between the two horizontal lines.

In the example, the price saving area is greater than the cost saving area. Thus there is a net decrease in the 'rent' received by producers in their role as owners of scarce resources. In this instance the cost savings in the variant accrue to the consumer and not to the producer. Whether this or the opposite effect occurs is determined by technical aspects of the situation. To investigate the matter, we must examine the changes in both the cost aggregates and the price aggregates.

We have seen that changes in cost aggregates are equal to the changes in the functional, as shown above. Price aggregates have also been calculated, and these have been compared with the base case prices to show savings to the consumer. This is covered in Tables 12 to 14, for the variant relative to the base case, and will be discussed in the next section.

(b) Substitution of Natural Gas by Oil (the variant case)

In the base case we allowed various substitutions between energy products. Thus, gas oil could replace low sulphur fuel oil, and natural gas heating oil up to specified limits in certain areas, such as Russian gas for ELFO (gas oil) in Germany. However, the base case did not feature any instance of oil directly replacing natural gas in the USA.

The variant is a demonstration of the use of the model to find the effect of changing a political constraint. Up to 30% of the demand for natural gas, in the USA only, is allowed to be replaced by naphtha, gas oil or low sulphur fuel oil. We are not concerned as how this is to be accomplished, whether by price changes, legislation or otherwise. In fact, in the optimum solution for this variant, the substitution of oil for gas was not pushed to the 30% limit allowed. Oil was substituted for gas only in the US East Coast region, the amount of gas demand replaced being 250.7 billion cubic meters or 23.8% of the total. Details of this substitution on the East Coast were:

Oil Products Replacing Gas	Million B/CD	Gas Replaced (as FOE) Million B/CD
Gas Oil	3.81	3.52
Low Sulphur Fuel Oil	0.91	0.91
Naphtha	0.08	0.07
TOTAL	4.80	4.50

where the totals are not in balance because of the lower heating values per barrel of the two lighter products, relative to FO; also the marginally higher heating value of LS FO relative to standard FO is disregarded.

In other parts of the world, including the other two US regions, the substitutions were in the opposite direction, with gas replacing liquid fuels at the following rates, in FOE units:

	Million B/CD
US Central and Gulf	0.90
US West Coast	0.07
Canada, West	0.02
Germany	0.69
Italy	0.39
France	0.17
	2.24

The gas-for-oil substitution in the US Central and Gulf Coast area is up to the maximum limit allowed, the solution indicating that the penalty imposed by this limit is, at the margin, equivalent to $0.67/bbl FO, and from this one can infer that the substitution of gas-for-oil beyond the permitted limit would save $0.67 for each bbl FOE replacing oil. In general, the inference is that it pays to use gas near its source, but with increasing distance from the source it becomes only economic as a premium fuel, and its use for non-premium purposes is a waste of resources.

World totals for the variant relative to the base case show gas consumption reduced by 0.96 million B/CD as FOE and crude oil increased by 0.73 million B/CD, giving a net saving in energy, due to the lower losses on LNG transportation and in refining, as a result of less cracking.

Returning to Table 2, we can see for the variant, relative to the base, that the world builds an additional 964,000 B/SD of crude distillation capacity, 717,000 B/SD less cat cracking, 510,000 B/SD less hydro-cracking capacity, and so on. Of particular interest is that none of the 1,892,000 B/SD SNG capacity of the base case is now required, and the LNG capacity (as FOE) is reduced by 1,072,000 B/SD or 23%. From the second part of the table, covering net capacity utilisation, the reduction in cat cracking capacity is twice as pronounced at 1,425,000 B/SD. The naphtha not required for SNG production can be reformed instead, reflecting additional building and utilisation of catalytic reforming capacity.

Table 4 shows the effect on capital requirement by area. Thus there is an increase of $23 million in Australia, a decrease of $478 million in the U K and Eire, and so on, to give a reduction in total refinery investment of $5.6 billion or about a quarter. It can be seen from the bottom of this table that more oil tankers are needed, adding $3.2 million, but this is more than balanced by a saving of $4.1 billion on LNG carriers. The overall capital requirement is reduced by $6.5 billion or about 15%.

The change in the functional, as already indicated, gives a cost saving of $1.986 billion per year, but the saving in real resources consumed is greater than this, because payments for marginal crude oils included in the functional have increased.

We will now consider the effects of the variant versus the base case on an aggregate basis, in terms of the consumer's annual bill, and the summarised results for all areas are given in Table 12, with derivations for four areas detailed in the two following tables. Thus per Table 13 for Australia the equilibrium price of gas/LPG in the base case was $2.920/bbl while in the variant it was $3.223/bbl giving a difference of $0.303/bbl. With the total consumption in both fixed at 3,708,000 Bbls/A, there is a change of $1,120,000/A in the total paid by the consumer in Australia for this product, and this is shown negatively to represent a loss to the consumer. Treating each product in the same way we find that the total increase in the Australian consumers' bill for petroleum products is $66.18 million, or an average of $0.216/bbl. All of the areas other than the USA were assessed in the same way, and somewhat incorrectly, by ignoring the change in products volumes between the two cases. But for the three US areas, the more exact calculations have been undertaken and are detailed in Table 14.

(c) Balance of Payments (incl. Shipping)

If we assume that natural gas is sold at its equilibrium price (this, of course, is not the case at present with price regulation) the total US wholesale bill for oil products and natural gas drops by $9.7 billion (Table 12). These findings are clearly relevant to the US balance of payments position. Full evaluation of the effect on balance of payments would require more detailed investigation, but these results establish that effects of the order of many billions of dollars per annum are possible. The aggregate effect on prices in all regions other than the United States represents increased payments by the consumer amounting to some $2.1 billion dollars per annum.

The effect of this variant on shipping is important for the overall interpretation of the results. This information is summarised in Table 3. Compared with the base case, the equilibrium freight rate from the Persian Gulf to Rotterdam rises for smaller vessels, e.g. from 97.3% to 130.6% of Worldscale for the under 25,000 dwt class. Total shipbuilding increases from 96.4 to 112.6 million dwt. Its composition also changes; vessels in the 50-80,000 and 80-125,000 dwt classes are now built. The number of LNG ships built decreases from 96 to 35. Shipping employed in the product trade rises from 38.3 to 51.9 million dwt.

The cost of transporting Arabian Light crude to its various destinations is increased. Details are given in Table 15. For example, to Australia the increase is $0.76/tonne, from $5.07/tonne in the base case to $5.83/tonne for the variant. These changes in freight rates are closely correlated with the changes in product prices in different regions, the largest price increases being associated with the largest increase in freight rates.

The overall picture presented by these various comparisons is as follows: If the United States uses its gas nearer its sources, and replaces some gas by oil in regions more distant from the gas sources, the following effects are brought about. World capital expenditure is significantly reduced and total resource use is decreased by more than $2 billion per annum. The US decreases its total wholesale bill for gas and oil products by almost $10 billions, but in doing so it requires greater oil product imports. This in turn requires more small-ship tonnage, raising the demand for small ships and hence their equilibrium freight rates, and this increases oil product prices throughout the rest of the world because of port restrictions on ship size. This and other effects raise the rest of the World's wholesale oil product bill by some $2.1 billion. The American consumer is better off, and so are the shipowners, but the rest of the world loses.

(5) CONCLUDING REMARKS

Our work has just begun and much more study is underway. This paper is but an illustration of one of the ways our model may be used. Whilst the paper suggests that the natural gas sector of the USA, and indeed the rest of the world, could well be investigated against many plausible scenarios in this way to determine the outcome of policy decisions, it is not suggested that legislation should be considered on this one run.

Having said this, there remains one point which can be stressed, a change in policy can have very significant effects on refinery investment plans, affecting both types of processes and locations. A World model is needed to provide input to allow corporations to plan efficiently.

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TABLES

1. New refinery capacities and plant utilisation, by area, base case.
2. New refinery capacities and plant utilisation, World totals, for the two cases.
3. Shipping analysis: Equilibrium freight rates and new shipping tonnages in the two cases.
4. Capital expenditure, the two cases.
5. Natural gas: Quantities and Equilibrium prices for the base case.
6. Equilibrium prices of products(wholesale) for the base case
7. Oil imports into the three US areas, by tanker size for the base case.
8. Oil Supply and Demand balance of the three US areas, base case.
9. Gas Supply and Demand balance of the three US areas, base case.
10. Available crude oil supplies in 1977 and associated qualities (gravities and sulphur contents).
11. Equilibrium prices of crude oils for the two cases, at oil fields
12. Totals for the 22 areas) Effect of changes in Equilibrium
13. Derivation for Australia) prices between the two cases on
14. Derivation for 3 US areas) the Consumer's Annual Bill.
15. Equilibrium freight rates from the Persian Gulf, $per tonne.

TABLE 1

NEW REFINERY CAPACITIES, BY AREAS BASE CASE '000 B/SD

Unused existing capacities shown negatively

AREA		CDU	VDU	CCU	CRU	ALK	H/C	H/F	RDS	SNG	LNG	REGAS	AREA
A	Australia		-249		3	9		-66					A
B	UK & Eire	453	267	331	72	66	18			2			B
C	Canada (E)	98		40		35	43	18		320			C
D	Canada (W)	100	-40		15	6		118		139			D
E	Medit'n	500		19	38	12	2	77			1830		E
F	France	624	440	296	282	61		225					F
G	Germany			85		29							G
H	Benelux		9	62	198	41		346					H
J	Japan	1615	-922		-31		34	221	98			209	J
K	Caribbean		84	148	131	20					1609		K
L	S America	-116	-60		-5	14		36					L
M	Mid East	2311	711	346	149	58	57	681					M
N	S Africa	258	133	69	31	6							N
P	Spain/Port	29	-22	29	26			20		20		41	P
Q	Siberia										55		Q
R	Russia												R
S	Scandinavia	62		19		9		-104					S
T	Italy	567	102	206	626	38		154					T
U	USEC	1938	400		-346	67	330			1211		2771	U
V	USWC	416	-536			44		16		187	806	582	V
W	W Africa	211	58	27		3		-5			267		W
X	US Central		698	-119		207			-18	13			X
Y	S Asia		-4	33	79	12	5	18	6				Y
Z	S E Asia		-4	106	23	9	20				89		Z
Total Built		9181	2902	1817	1673	746	509	1930	104	1892	4656	3603	
Unused Capacity		-115	-1837	-120	-382	NIL	NIL	-175	-18	NIL	NIL	NIL	
Nett used		9066	1065	1697	1291	746	509	1755	86	1892	4656	3603	

TABLE 2

NEW REFINERY CAPACITIES & PLANT UTILISATION

WORLD AGGREGATES

BOTH CASES

(Capacities in '000 B/SD)

	NEW CAPACITY TO BE BUILT		NET CAPACITY UTILISED	
	Base Case	Variant: Oil Subst for N Gas (changes)	Base Case	Variant: Oil Subst for N Gas (changes)
Crude distillation	9181	964	9056	815
Vacuum distillation	2906	-1571	1066	-1974
Catalytic cracking	1817	-717	1697	-1425
Catalytic reforming	1673	931	1291	1285
Alkylation	746	-352	746	-352
Hydrocracking	509	-509	509	-509
Hydrofining	1930	863	1755	870
Residue Desulph	104	-20	86	-20
Substitute Nat Gas	1892	-1892	1892	-1892
Liquifaction Nat Gas	4656	-1072	4656	-1072
Regassing Nat Gas	3603	-750	3603	-750

Base Case capacities in Col. 3 represent Total new plane less unused capacity.

Variant capacities in Cols. 2 and 4 are differences from the base case, with the capacity reductions shown negative.

Substitute Natural Gas capacities expressed in terms of Naphtha feed input requirement.

Natural Gas in LNG operations, as Fuel oil equivalent, with 1 bbl FO = 6.2 million BTU.

TABLE 3

SHIPPING ANALYSIS

EQUILIBRIUM FREIGHT RATES & NEW SHIPPING TONNAGE

	BASE CASE	VARIANT CASE
WORLD SCALE RATES FOR FREIGHT		
(Persian Gulf to Rotterdam)		
25,000 dwt vessels	97.3	130.6
25-50,000 " "	86.6	113.5
50-80,000 " "	86.1	113.1
80-125,000 " "	73.3	84.4
125-200,000 " "	69.6	69.6
200,000 " "	60.4	60.4
NEW TANKER TONNAGE TO BE BUILT ø		
(Million DWT)		
25,000 dwt vessels	(ø67.3)	(ø49.9)
25-50,000 " "	(ø28.4)	(ø14.2)
50-80,000 " "	(ø14.1)	9.2
80-125,000 " "	(ø5.8)	0.8
125-200,000 " "	1.6	4.4
200,000 " "	94.8	98.2
Tonnage total	96.4	112.6
TONNAGE USED TO CARRY PRODUCTS		
(Million DWT)		
25,000 dwt vessels	1.8	3.6
25-50,000 " "	14.9	15.0
50-80,000 " "	21.6	33.3
Tonnage total	38.3	51.9
NUMBER OF LNG CARRIERS (all of 125,000 m^3 capacity)	96	35

ø Where no new tonnage is called for, the figures in brackets are the penalties in ø/dwt that would be incurred by building tankers in the categories referred to.

TABLE 4

CAPITAL EXPENDITURE

$ Million

	Base Case (a)	Variant Case (b)	Difference (b)-(a)
REFINING CAPITAL			
Australia	15	38	23
UK & Eire	591	113	-478
Canada, West	488	125	-362
Canada, East	212	75	-137
Mediterranean	4,156	4,141	-15
France	815	503	-312
West Germany	102	60	-42
Benelux	367	434	67
Japan	792	714	-78
Caribbean	3,677	3,887	210
South America	36	26	-10
Middle East & E Africa	1,592	1,564	-28
South Africa	174	131	-43
Spain & Portugal	84	75	-9
Russia, West	NIL	NIL	NIL
Russia, Siberia	119	119	NIL
Scandinavia	45	NIL	-45
Italy	868	1,815	947
USA, East Coast	3,424	796	-2,628
USA, West Coast	2,258	170	-2,088
USA, Central & Gulf	403	379	-24
East Africa	662	155	-507
S Asia	116	113	3
S E Asia	342	278	-64
Refinery Total	21,338	15,711	-5,627
OIL TANKERS	12,564	15,810	3,246
LNG CARRIERS	6,474	2,380	-4,094
TOTAL CAPITAL	40,376	33,901	-6,475

TABLE 5

NATURAL GAS

BASE CASE

QUANTITIES & EQUILIBRIUM PRICES

Natural Gas Field	AVAILABLE GAS SUPPLIES	UNUSED SUPPLY	EQUILIBRIUM PRICES
	Million Bbls/CD (FOE)	Million Bbls/CD (FOE)	$/Bbl FO equivalent
Australia	0.359	0.170	0
Brunei	0.359	-	0.38
Canada	1.848	-	4.43
Caribbean	1.435	-	2.05
France	0.179	-	3.36
Germany	0.413	-	3.34
Italy	0.269	-	3.44
Japan	0.126	-	4.02
Mediterranean	1.973	-	1.51
Netherlands	1.704	-	3.19
North Sea (Norway)	0.224	-	5.05
North Sea (UK)	0.735	-	5.13
Pakistan	0.359	0.208	0
Persian Gulf	1.346	0.816	0
Russia (Western)	9.867	-	1.70
Siberian Russia	0.144	0.093	0
US Gulf Coast	11.302	-	5.02
Alaska	0.718	-	0.92
West Africa	0.359	-	1.05
Total	33.719	1.287	

The gas quantities have been expressed as bbls fuel oil equivalent, with 1 bbl FO = 6.2 million BTU.

TABLE 6

PRODUCT EQUILIBRIUM PRICES

$/ PER BBL

Wholesale Basis

BASE CASE

	REFINERY GAS & LPG	LDF	MOTOR GASOLINE			KERO/ATK	GAS OIL	FUEL OIL			Bitumen
			Premium	Regular	Lead free			L Sulphur	M Sulphur	H Sulphur	
Austral	2.92	3.48	4.68	4.55	4.78	3.01	2.27	2.82	2.81	2.79	2.90
UK	3.48	4.27	5.36	5.22	5.47	3.74	2.97	3.39	3.39	3.31	3.45
E Canada	3.54	4.57	5.76	5.66	5.83	3.48	3.04	3.50	3.49	3.38	3.48
W Canada	3.27	3.75	5.00	4.90	5.04	3.88	4.00	4.16	4.06	3.72	3.62
Medit	3.27	4.03	5.02	4.93	5.18	3.16	2.74	3.03	3.09	3.13	3.27
France	3.38	4.23	5.36	5.20	5.46	3.07	3.08	3.38	3.34	3.23	3.35
Germany	3.87	4.33	5.45	5.38	5.52	3.21	3.25	3.50	3.43	3.35	3.51
Benelux	3.35	4.21	5.32	5.20	5.45	3.08	3.12	3.49	3.38	3.20	3.32
Japan	3.47	3.79	4.26	4.24	4.32	3.89	2.88	3.13	3.05	2.63	3.23
Cent Am	3.10	4.32	5.46	5.39	5.64	3.25	2.88	3.25	-	2.96	2.95
So. Amer	3.21	4.19	4.61	4.65	4.74	3.59	2.78	2.95	-	3.06	3.20
Mid East	2.05	3.35	4.29	4.25	4.38	2.93	1.76	2.26	-	1.96	2.05
S Africa	2.83	3.74	4.78	4.61	4.90	2.75	2.37	2.64	-	2.70	2.80
Spain	3.54	3.93	4.94	4.84	5.04	3.37	3.19	3.41	3.43	3.42	3.61
Scandin	3.60	4.28	5.47	5.39	5.54	3.42	3.10	3.56	3.49	3.34	3.63
Italy	3.22	4.19	5.29	5.12	5.33	3.00	2.81	3.12	3.12	3.08	3.22
US EC	3.59	4.54	5.77	5.68	5.86	3.49	3.17	3.62	3.52	3.22	3.46
US WC	3.35	4.27	5.47	5.38	5.54	3.86	3.25	3.54	3.47	3.20	3.07
W Africa	3.26	4.24	5.14	4.99	5.28	3.31	2.95	3.19	-	3.11	-
US Gulf	3.01	4.60	5.82	5.68	5.88	3.33	2.88	3.29	3.19	2.88	2.75
S Asia	2.85	3.25	4.08	4.03	-	3.17	2.01	2.66	-	2.33	2.44
S E Asia	3.10	3.49	4.32	4.29	-	3.38	2.23	2.72	2.65	2.50	2.86

TABLE 7

OIL IMPORTS INTO THE THREE US AREAS

'000 B/CD

BASE CASE

	TO U.S EAST COAST			TO U.S GULF COAST			TO U.S WEST COAST				
TANKER SIZE ('000 dwt range)	<25	25-50	50-80	<25	25-50	50-80	<25	25-50	50-80	80-125	125-200
CRUDE OILS											
Bachaquero	130				575						
Oficina					348						
Tia Juana	972				87						
Ecuador								215			
Alaska (South)							6	294			
Minas (S E Asia)										84	127
Arabian Light											397
Qatar Export			195								
Nigerian Light		208	511								
Mandji blend			95								
Hassi Messaoud	287	274									
Arzew	17										
TOTAL	1,406	482	801		1,010		6	509		84	524
PRODUCTS											
Premium Gasoline		509							284		
Regular Gasoline		459	587						75		
Clear Gasoline		117									
LDF		281	18			700			309		
Kerosine		335	17				69		11		
Gas Oil		247							72		
Low S Fuel Oil	160	1,128									
TOTAL	160	3,076	622			700	69		751		

TABLE 8

THE THREE U.S AREAS

OIL SUPPLY & DEMAND 1977

Millions Bbls/Calendar Day

BASE CASE

	EAST COAST	CENTRAL & GULF	WEST COAST	TOTAL U S A
CRUDE OIL				
Domestic production	0.73	7.20	1.27	9.20
Imports - Canada	0.21	0.79	-	1.00
" - Rest of W Hemisphere	1.10	1.01	0.30	2.41
" - E Hemisphere	1.59	-	0.61	2.20
Total Imports	2.90	1.80	0.91	5.61
Total Processed (incl domestic)	3.63	9.00	2.18	14.81
NATURAL GAS LIQUIDS				
Domestic production	NIL	1.70	NIL	1.70
Imports - Canada	"	0.13	"	0.13
		1.83		1.83
Total Crude & NGL	3.63	10.83	2.18	16.64
Cracked spirit returns	0.01	0.12	0.01	0.14
TOTAL INPUT TO US REFINERIES	3.64	10.95	2.19	16.78
REFINED PRODUCTS				
Gas & LPG (FOE)	0.16	1.33	0.09	1.58
Motor Spirit: Domestic Prodn	0.63	4.10	0.78	5.51
Non-US imports	1.67	-	0.36	2.03
Light distillate to SNG	1.12	0.01	0.17	1.30
LDF: Domestic production	-	0.36	0.02	0.38
Non-US imports	0.30	0.70	0.31	1.31
ATK: Domestic production	-	0.70	0.20	0.90
Non-US imports	0.35	-	0.08	0.43
Gas Oil: Domestic production	0.74	2.23	0.22	3.19
Non-US imports	0.25	-	0.07	0.32
Fuel Oil: Domestic production	0.62	0.95	0.36	1.93
Non-US imports	1.29	-	-	1.29
Bitumen & Coke	0.16	0.42	0.13	0.71
Output from US refineries	3.43	10.10	1.97	15.50
Non-US imports	3.86	0.70	0.82	5.38
	7.29	10.80	2.79	20.88
Total Area Product Demand	9.00	9.05	2.83	20.88
Total Refinery gas, fuel & loss	0.21	0.85	0.22	1.28
Total Consumption (including Refinery fuel & loss)				22.16

TABLE 9

NATURAL GAS SUPPLY & DEMAND BALANCE

FOR THE THREE U.S AREAS BASE CASE

In Units of Million B/CD of Fuel Oil equivalent

	EAST COAST	CENTRAL & GULF	WEST COAST	U S TOTAL
Domestic Natural Gas	10.354	0.386	-	10.740
Domestic SNG production	1.034	0.013	0.160	1.207
LN				
LNG shipments from Southern Alaska	-	0.140	0.379	0.519
Imports by pipeline from Canada	1.393	-	-	1.393
Imports of LNG (excl. Alaskan)	2.473	-	-	2.473
Total Supply =(Total domestic demand)	15.254	0.539	0.539	16.332

It is assumed 1 bbl fuel oil = 6.2 million BTU.

The above delivered quantities are after transmission losses of approximately 5% for pipeline gas, domestic and Canadian, and around 20% for LNG imports, being lower for the Alaskan LNG than the rest, the longer haul LNG imports.

TABLE 10

CRUDE OIL SUPPLIES IN 1977 AVAILABILITIES & BASIC QUALITIES

	'000 B/CD	°API	SULPHUR %wt
NORTH SEA			
Forties (UK)	820	36.6	0.28
Ekofisk (Norway)	711	35.0	0.20
AFRICA			
Libya - Es Sider	616	36.9	0.38
" - Brega	312	39.2	0.24
" - Zueitina	212	41.8	0.21
" - Sarir	722	37.6	0.14
" - Nafoora (Amna)	306	35.4	0.21
Algeria - Arzew	641	43.6	0.10
" - Hassi Messaoud	643	44.0	0.15
" - Zarziaitine	106	41.5	0.09
Nigerian - Light	1,238	37.6	0.13
" - Medium	671	25.7	0.24
W Africa, Gabon, Mandji	239	31.4	0.68
MIDDLE EAST			
Kuwait Export	3,378	31.3	2.5
Kuwait N Zone, Khafji	488	28.6	2.85
Arabian - Light	20,270	34.7	1.70
" - Heavy	2,723	28.0	2.85
Iranian - Light	5,040	33.6	1.36
" - Heavy	2,974	31.0	1.60
Iraq - Basra	1,100	34.0	1.95
" - IMEG A	1,020	36.05	1.88
Abu Dhabi - Murban	1,877	39.4	0.74
" - Zakum	721	37.3	1.36
" - Umm Shaif	309	37.0	1.38
Qatar - Export	206	41.8	1.05
" - Marine	309	37.0	1.50
Oman	401	32.8	1.25
Egypt/El Morgan	697	31.7	1.66
Syria	286	24.8	3.50
FAR EAST			
Indonesia - Minas	1,946	36.4	0.10
Australia - Gippsland	432	44.2	0.09

Table continued overleaf

TABLE 10
(2nd page)

	'000 B/CD	°API	SULPHUR %wt
USA			
Bradford, Pa	61	41.0	0.10
Texas Gulf - Heavy	551	31.0	0.15
" " - Light	210	41.1	0.07
" East	1,450	37.8	0.29
" West Med	1,665	33.5	1.26
" " Sour	1,200	31.0	1.98
Louisiana	2,594	32.2	0.24
Arkansas/Mississippi	201	32.8	1.55
California Blend	570	25.0	0.95
Alaska South	300	33.8	0.09
CANADA			
IPPL Mixed Sweet	794	38.5	0.27
" " Sour	352	37.9	0.46
" Light "	403	35.9	1.00
Bantry	166	24.8	2.37
Rainbow	197	38.5	0.75
Marguerite Lake	180	12.0	3.92
CENTRAL AMERICA			
Venezuela - Bachaquero	1,298	14.2	2.62
- Oficina	403	33.8	0.77
- Tia Juana	1,350	26.5	1.54
SOUTH AMERICA			
Ecuador	215	28.6	0.94

TABLE 11

CRUDE OIL EQUILIBRIUM PRICES — THE TWO CASES

Relative to Arabian Light crude oil @ $1.96/Bbl,FOB
All values in $/Bbl, at source, with differentials in Cents/Bbl.

	BASE CASE	VARIANT CASE	CHANGE RELATIVE TO BASE CASE
	(a)	(b)	(b)-(a)
	($/Bbl)	($/Bbl)	(¢/Bbl)
NORTH SEA			
Forties	3.131	3.303	17.2
Ekofisk	3.131	3.340	20.9
AFRICA			
Libya - Es Sider	2.911	3.128	21.7
" - Brega	2.976	3.167	19.1
" - Zueitina	2.968	3.302	33.4
" - Sarir	2.914	3.174	26.0
" - Nafoora (Amna)	2.880	3.177	29.7
Algeria Arzew	3.022	3.209	18.7
" - Hassi Messaoud	3.084	3.199	11.5
" - Zarzaitine	3.027	3.206	17.9
Nigerian Light	2.865	3.085	22.0
" - Medium	2.823	3.206	38.3
W Africa, Gabon, Mandji	2.722	3.043	32.1
MIDDLE EAST			
Kuwait Export	(see bottom of Table)		
" -N Zone - Khafji	1.911	1.907	-0.4
Arabian Light	(see bottom of Table)		
" -Heavy	(" " " ")		
Iranian Light	(" " " ")		
" -Heavy	(" " " ")		
Iraq - Basra	1.938	1.930	0.8
" - IMEG A	2.759	2.838	7.9
Abu Dhabi - Murban	2.075	2.101	2.6
" " - Zakum	2.052	2.062	1.0
" " - Umm Shaif	2.075	2.063	-1.2
Qatar - Export	2.071	2.047	-2.4
- Marine	2.004	2.012	0.8
Oman	2.104	2.120	1.6
Egypt/El Morgan	1.942	1.942	NIL
Syria	2.809	2.936	12.7
FAR EAST			
Indonesia - Minas	2.360	2.556	19.6
Australia - Gippsland	2.641	2.857	21.6

Table continued overleaf

TABLE 11
(2nd page)

	BASE CASE	VARIANT CASE	CHANGE RELATIVE TO BASE CASE
	(a)	(b)	(b)-(a)
	($/Bbl)	($/Bbl)	(¢/Bbl)
USA (incl. Alaska)			
Bradford, Pa	3.410	3.854	44.4
Texas Gulf - Heavy	3.324	3.979	65.5
" " - Light	3.383	3.862	47.9
" East	3.504	3.881	37.7
" West Med	3.339	3.598	25.9
" " Sour	3.467	3.640	17.3
Louisiana	3.546	4.011	46.5
Arkansas/Mississippi	3.260	3.499	23.9
California Blend	3.139	3.286	15.3
Alaska, South	3.246	3.372	12.6
CANADA			
IPPL mixed sweet	3.584	3.938	35.4
" " sour	3.552	3.881	32.9
" light "	3.398	3.630	23.2
Bantry	3.247	2.534	28.7
Rainbow	3.461	3.732	27.1
Marguerite Lake			
CENTRAL AMERICA			
Venezuela - Bachaquero	2.772	3.072	30.0
- Oficina	3.209	3.448	23.9
- Tia Juana	2.949	3.232	28.3
SOUTH AMERICA			
Ecuador	2.635	2.683	4.8

For the five marginal crudes, given F.O.B. values and maximum availabilities, the computer solution indicates how much of the crude oils shoule be lifted.

		'000 B/CD		
			Computer Solutions	
	$/BBL	MAX AVAILABILITY	BASE CASE	VARIANT CASE
Arabian Light	1.96	20,270	18,630	17,902
Arabian heavy	1.90	2,723	237	523
Kuwait export	1.91	3,373	2,714	2,516
Iranian Light	1.99	5,040	3,294	5,040
Iranian Heavy	1.98	2,974	2,667	2,187

TABLE 12

EFFECT OF CHANGING EQUILIBRIUM PRICES ON CONSUMER'S ANNUAL BILL

Variant relative to Base Case

$ Million/year

East Coast	(U)	9387
Central & Gulf	(X)	11
West Coast	(V)	306
USA TOTAL		9704
Australia	(A)	-66
UK & Eire	(B)	266
Canada E	(C)	327
Canada W	(D)	120
Mediterranean	(E)	-277
France	(F)	-318
W Germany	(G)	-149
Benelux	(H)	-225
Japan	(J)	-847

Cent Am & Carib	(K)	-148
South America	(L)	-184
Middle East	(M)	-29
South Africa	(N)	-23
Spain/Portugal	(P)	-71
Scandinavia	(S)	-144
Italy	(T)	-231
W Africa	(W)	2
S Asia	(Y)	-72
S E Asia	(Z)	-18

USA	9704
Rest of World	-2087
TOTAL	7617

TABLE 13

EFFECT OF CHANGING EQUILIBRIUM PRICES ON CONSUMER'S ANNUAL BILL

Variant relative to Base Case

Australia

	EQUILIBRIUM PRODUCT PRICES ($ PER BBL)			MILLIONS BBLS PER YEAR	$ MILLION PER YEAR
	BASE CASE (a)	VARIANT (b)	(a)-(b)		
Gas	2.920	3.223	-0.303	3.7	-1.12
LDF	3.480	3.475	0.005	6.7	0.04
PMS	4.681	4.682	-0.001	86.1	-0.10
RMS	4.548	4.582	-0.034	11.6	-0.39
CMS	4.778	4.779	-0.001	9.0	-0.01
Kero	3.012	3.083	-0.071	21.3	-1.51
Gas Oil	2.268	2.697	-0.429	65.3	-28.01
LS FO	2.819	3.213	-0.394	43.6	-17.16
MS FO	2.813	3.154	-0.341	21.0	-7.17
HS FO	2.789	3.077	-0.288	33.6	-9.67
Bitumen	2.897	3.148	-0.251	4.3	-1.08
		TOTALS		306.2	-66.18

Average price rise: $0.216 per Bbl

TABLE 14

EFFECTS OF CHANGING EQUILIBRIUM PRICE ON THE CONSUMER'S ANNUAL BILL

Variant case relative to base case — THE THREE US AREAS

	U.S EAST COAST					US GULF & CENTRAL				
	Base Case (a)		Variant (b)		Annual Change	Base Case (a)		Variant (b)		Annual Change
	$/ Bbl	Mill Bbl/A	$/ Bbl	Mill Bbl/a	$ Mill (a)-(b)	$/ Bbl	Mill Bbl/A	$/ Bbl	Mill Bbl/A	$ Mill (a)-(b)
LPG etc.	3.591	40.8	4.190	40.8	-24.42	3.011	72.7	3.565	72.7	-40.28
LDF	4.536	109.2	4.330	109.2	22.49	4.603	384.0	4.604	384.0	-0.45
PMS	5.773	238.7	5.600	238.7	41.29	5.817	351.5	5.640	351.5	62.21
RMS	5.677	600.0	5.531	600.0	87.60	5.677	886.8	5.531	886.8	129.47
CMS	5.865	91.9	5.665	91.9	18.37	5.877	135.1	5.700	135.1	23.92
Kero	3.486	201.0	4.001	201.0	-103.53	3.300	164.6	4.007	164.6	-116.38
Gas Oil	3.171	644.0	4.149	2116.5	-6739.44	2.875	502.1	3.748	147.1	892.35
LS FO	3.615	581.3	4.468	920.6	-2011.90	3.286	154.3	4.021	154.3	-113.39
MS FO	3.524	177.2	4.307	177.2	-138.78	3.188	47.8	3.850	47.8	-31.76
HS FO	3.217	38.8	3.821	38.8	-23.46	2.874	-	3.356	-	-
Bitumen	3.465	53.8	3.900	53.8	-23.40	2.753	115.0	3.429	115.0	-77.75
Nephtha	5.373	-	3.997	29.1	116.32	4.282	-	4.342	-	
OIL TOTAL		2776.7		4617.6	-9011.50		2813.9		2458.9	727.94
NAT. GAS	6.469	5567.5	4.487	3926.4	18398.57	5.345	196.5	3.364	525.3	-716.81
		8344.2		8544.0			3010.4		2984.2	
NET EFFECT					9387.07					11.13
					= $9.387 billion					= $0.011 billion

Natural gas quantities expressed as Fuel oil equivalents, taking 1 bbl FO = 6.2 million BTU

The equilibrium product prices are given in $ per Bbl in the first and third columns of the three sections.

Overleaf: U S West Coast

TABLE 14
(2nd page)

	U S WEST COAST				
	Base Case (a)		Variant (b)		Annual Change
	$/ Bbl	Mill Bbl/A	$/ Bbl	Mill Bbl/A	$ Mill (a)-(b)
LPG, etc.	3.347	22.2	3.653	22.2	-6.81
LDF	4.274	120.0	4.380	120.0	-12.73
PMS	5.466	104.3	5.397	104.3	7.20
RMS	5.376	258.3	5.322	258.3	13.95
CMS	5.538	40.3	5.471	40.3	2.70
Kero	3.860	106.3	3.337	106.3	55.62
Gas Oil	3.252	114.8	3.270	88.5	83.90
LS FO	3.544	102.6	3.899	102.6	-36.41
MS FO	3.468	26.3	3.806	26.3	-8.88
HS FO	3.195	4.5	3.487	4.5	-1.32
Bitumen	3.072	22.9	3.584	22.9	-11.72
Naphtha		-	3.149	-	-
OIL TOTAL		922.5		896.2	85.50
NAT GAS	4.581	218.5	3.535	220.7	220.64
		1141.0		1116.9	
NET EFFECT					306.14

= $0.306 billion

TABLE 15

EQUILIBRIUM FREIGHT RATES FROM THE PERSIAN GULF

$ PER TONNE

DESTINATION	BASE CASE	VARIANT CASE
Australia	5.07	5.83
UK and Eire	8.00	9.32
Canada	9.41	10.95
Mediterranean	6.38	7.49
France	7.38	8.29
Germany	8.42	9.59
Benelux	7.16	8.20
Japan	5.54	7.44
Caribbean	7.50	9.18
South America	8.44	10.59
South Africa	4.00	5.26
Spain & Portugal	7.84	9.43
Scandinavia	8.43	9.84
Italy	6.54	7.85
USA (East Coast)	10.24	12.10
USA (West Coast)	8.65	9.66
West Africa	7.10	9.54
USA (Central)	9.99	11.92
S Asia	2.36	3.20
S E Asia	4.20	5.06

Discussion

Mr. Krymm (IAEA) had two questions. First, he asked whether he had understood correctly that the demand for different oil products is treated exogenously and whether the model calculates the ratios of prices for different products depending on the price of crude oil. Finally, he asked how the increasing price of crude oil changed the results. Mr. Deam replied that he had the first point right, and refferring to the second question, he said that there are one or two things which are politically too sensitive to be reported as yet.

Mr. Manne (IIASA) had one comment on the methodology concerning the appropriateness of different degrees of geographical detail for different planning horizons. He remarked that it sounded to him as though the model is a very appropriate one for a five-year-ahead type of planning, and that Mr. Deam himself had agreed that this is probably not the kind of model he would want for 1985 or beyond. It is true that one does not have to make vacuum distillation decisions for 1985 now, but one does have to make nuclear power plant decisions which are long-term investment decisions. Then he stressed that he wondered whether this does not go back to the very important initial question raised by Mr. Deam during his presentation, namely which favorite location in the world should be chosen as the world's marginal sources of crude supply. Furthermore, he said that, in addition to the Arabian peninsula, he can nominate a place for shale oil supplies somewhere in the Rocky Mountains and that this, at a price of $10 per barrel, may be another kind of marginal source. He said also that one does not need to do much more than a back-of-the-envelope conclusion to see that a price of $10 is irrational if one can buy infinite amounts of oil with a price of $2 per barrel, but that it is not irrational to build nuclear power plants. Mr. Deam replied that there are two things he can pick out. First, he said that he does not think about what the next source of marginal crude is; it may well be available. Finally, he noted that there is no point in arguing about presenting ideas for the year 2000; the only thing he worries about for the year 2000 is that he probably has not got the options and that he does not know all about the technology. Mr. Manne then asked why he did not include shale oil where one has a technology for supplying crude. Mr. Deam replied that many people in the oil industry do not approve of this approach. He mentioned further that one can, of course, consider shale and tarsands, etc., and try to locate the next source of crude with the model, but the marginal weak in the world is that it is a very transitory situation--and the energy world is determined by a transitory situation. One does not have the knowledge of how long the light Arabian fuel will last. Finally, he noted that real energy debate is locating the marginal source of energy; thus the main problem is when this model begins to sort those questions.

INTERFUEL SUBSTITUTION AND TECHNOLOGICAL CHANGE*

Kenneth C. Hoffman and Ellen A. Cherniavsky

Abstract

The trend towards increased electrification of the United States' energy system has been driven largely by the very rapid growth of energy demand sectors such as air-conditioning, industrial drive, and residential and commercial appliances. The goal of the United States to become more self-sufficient in energy could contribute significantly to the continuation of this trend. One possible self-sufficiency strategy involves generating increased amounts of electricity from coal and nuclear fuel to substitute for oil and gas. Technological change in end use sectors involving the electric automobile and the use of synthetic fuels derived from off-peak electric power can contribute significantly to the feasibility of this strategy.

The feasible range of partition of the energy system between electric and non-electric energy forms are evaluated in a quantitative manner using a linear programming model. Ranges of substitution of electric energy for non-electric energy forms are determined for the years 1985 and 2000 and the implications are evaluated in terms of resource usage, cost, and emissions of air pollutants.

*Work performed under the auspices of the U.S. Atomic Energy Commission for presentation at the Energy Modelling Conference, International Institute for Applied Systems Analysis, Austria, May 1974.

INTRODUCTION

In 1960 the United States consumed 16.6% of its energy resources for the production of electrical energy. Over the last decade, the annual growth rate in the electric sector was around 7%, about twice the level of growth in total energy resource consumption, and by 1969 this sector accounted for about 21.7% of all energy resources consumed. Much of this trend towards increased electrification is attributable to increased demand in end use sectors that are virtually totally dependent on electrical energy, such as air conditioning, residential and commercial lighting and appliances, and increased mechanization in industry using electric motor drive.

The future trend in the partition of the energy system between electric and non-electric secondary energy forms will depend in part on the relative growth in various end use sectors, but will also be influenced greatly by national policies and technological change. The penetration of such technologies as electric automobiles, hydrogen and hydrogen based synthetic fuels for mobile and stationary applications, and fuel cells would contribute to even greater levels of electrification than are now evident. Further, electrical energy may be substituted with existing technologies in several end use categories that are now served predominantly by fossil fuels used directly. Space heating and industrial process heat are prime examples of such categories.

The role of the electric sector in the United States' energy system is an extremely important policy issue as the nation strives to be more self-sufficient in energy resources. The abundant domestic resources of coal, nuclear fuel, and geothermal energy are at present best employed for the production of electricity and, in the near term, can contribute to self-sufficiency only if electrical energy is substituted for imported oil and gas. In the longer term, the development of economical coal gasification and liquefaction processes and the direct use of nuclear heat for chemical processes will provide a non-electric alternative.

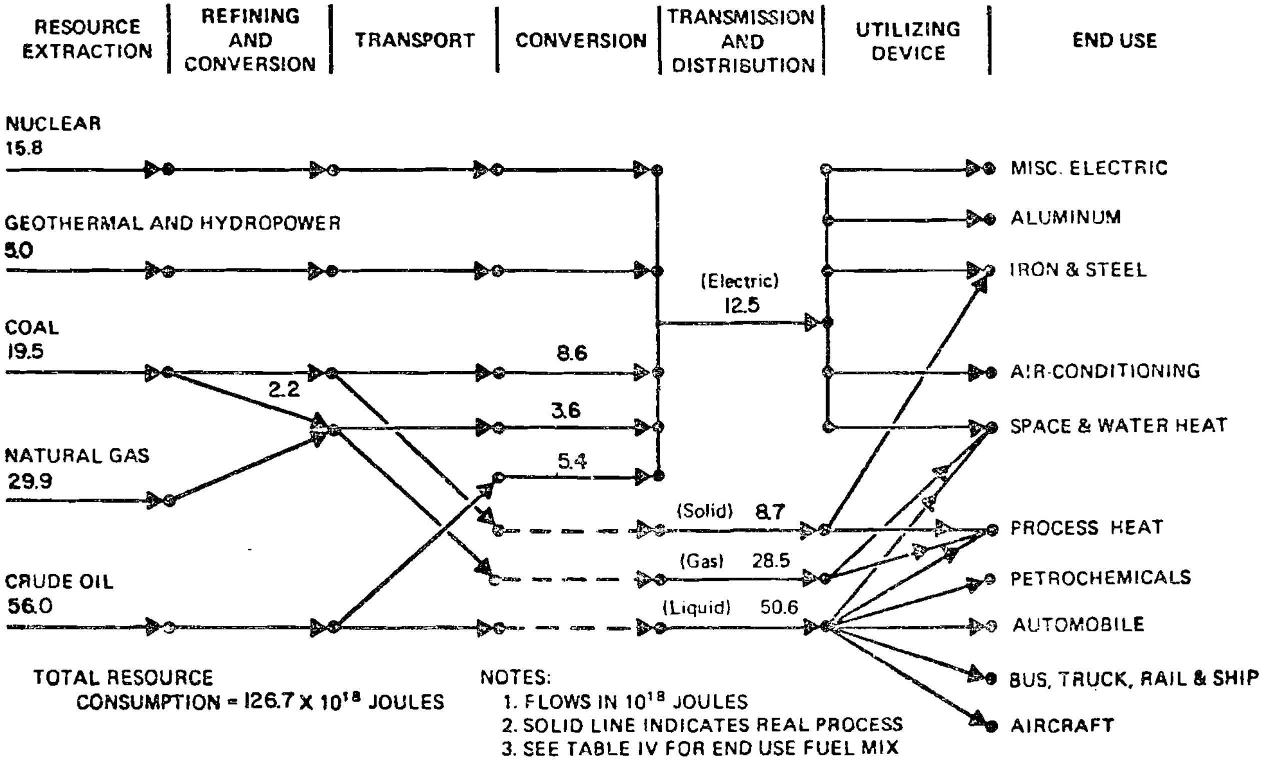
An analysis has been performed to determine the feasible range of partition of the energy system between electric and non-electric energy forms and the specific technological changes and interfuel substitutions that can affect that partition. The analysis employed a linear programming model of the energy system, described in the following section, that includes explicit technological detail and the relative efficiencies of various energy forms that may be applied to specific end uses. The load structure of the end use categories that may be electrified is also reflected in the model. The total annual cost and emissions of alternative partition configurations are discussed in a later section of this report.

DESCRIPTION OF ANALYTICAL MODEL

A linear programming model of the U.S. energy system (1) is used as the basic analytical technique in this study. The model includes provision for the full range of interfuel substitution, including substitution between electric and non-electric energy forms. It encompasses the entire energy system including all resources and demand sectors. Since the range of interfuel substitutability that is feasible depends on the supply and utilization technologies that are available, the model is constructed around the characteristics of these technologies. The technology related parameters that appear explicitly in the model are the efficiencies of energy conversion, delivery, and utilization devices; the emissions produced by the devices; and their cost. The intent in establishing the scope of the model is to include the technical elements that are felt to be of major importance in a framework that is as simple as possible. Simplicity is a requirement if all assumptions are to be evident and the results easily interpreted.

The energy system may be represented in a network format as shown in Figure 1. The network in this case is quantified with a set of projected energy flows for the year 1985 from alternate resources through the various energy conversion and delivery activities to specific end uses. Each link in the network represents a process or mix of processes used for a given activity, such as the refining of crude oil. Cost, efficiency and emission coefficients may be associated with each link. The energy flows indicated in Figure 1 reflect the technical efficiencies of the individual processes and thus the flows decrease progressively through the network. The projected energy flows correspond to several projections that had been prepared (2,3) earlier to indicate the degree of reliance on imported fuels that might result unless action were taken to move toward self-sufficiency. This earlier projection will be used in this study as a Base Case, or point of departure, for the development of alternative configurations. The links shown in the network diagram reflect only existing technologies. Using the linear programming model, alternative energy flows are determined which employ new technologies and which also involve the substitution of domestic resources to replace imported oil and gas.

The model determines the optimal energy flows within the energy demand and resource supply constraints that are applied for a particular analysis. The output of the analysis includes



TOTAL RESOURCE CONSUMPTION = 126.7 X 10^{18} JOULES

NOTES:
1. FLOWS IN 10^{18} JOULES
2. SOLID LINE INDICATES REAL PROCESS
3. SEE TABLE IV FOR END USE FUEL MIX

ENERGY SYSTEM NETWORK (1985 CASE I)

Figure 1

the total annual cost of service and an inventory of emissions to the environment associated with a given energy flow solution. Examination of the energy demand sectors at the right-hand side of the network indicates the degree of disaggregation included in the analysis. The substitution possibilities are dependent on these functional end uses and are quite different between the air-conditioning, automotive, and process heat categories, for example. The load-duration structure of electrical demands is also reflected in the model since the type of electric generating equipment employed is dependent on the portion of the load curve that it is to operate on. This is an important consideration in substituting electric energy for other fuels in such categories as space heating and transportation where there are significant peak demands.

The optimization of the energy system is performed with respect to cost and the objective is to minimize the cost of service, subject to policy, economic, and other constraints that may be represented in the objective function and constraint equations. Amortized capital costs, fuel costs, and other operating costs are included. A fixed charge rate of 15% is used for capital costs. Additional constraints are included to reflect existing systems that would not be replaced and to specify certain fuel uses that will probably occur for special reasons, such as regional viability, that are not reflected in an overall cost optimization of the U.S. energy system.

The technical efficiencies and environmental coefficients used in the analysis are taken from recent studies performed for the Council on Environmental Quality (4) and by the Environmental Protection Agency (5). The basic fuel costs used in the analysis are summarized below. The output of the analysis includes the sensitivity information that is needed to judge the effect of price changes for a given fuel on the optimal allocation of energy supplies. Sensitivity information is also developed concerning the effect of changes in the efficiency of energy conversion technologies.

FUEL COSTS (1970 dollars)

Coal	9.04	$\$/\text{metric ton}$	$(8.20\ \$/\text{ton})$
Oil	6.50	$\$/\text{barrel}$	$(6.50\ \$/\text{barrel})$
Natural Gas	15.20	$\$/1000\ M^3$	$(0.43\ \$/10^3 ft^3)$
Nuclear Fuel	0.19	$\$/10^9$ joules	$(0.20\ \$/10^6\ \text{Btu})$

The linear programming methodology is rich in economic interpretation. Of particular interest is the marginal value or "shadow price" of scarce resources in a given solution. These represent the unit change in overall cost of the system resulting from a unit change in availability of given resources. They are dependent on the cost differential between the scarce resource and a more costly but abundant substitute as well as on the relative technical efficiencies of the alternatives. The shadow prices provide a measure of the economic equilibrium of the system in terms of a comparison of the cost of expanding capacity of a given type with the value of that additional capacity. They may also be used to assess the structural changes that might occur in response to changes in economic values assumed in a given analysis. The output for a given analysis also provides an extensive study of the range of cost and efficiency over which given technologies are competitive. For purposes of clarity and brevity, however, only the primary output of the analyses is presented in this paper.

SUMMARY

The influence of interfuel substitution in specific end uses and of technological change on the partition of the energy system between electric and non-electric energy forms was determined in two series of computer runs performed for the years 1985 and 2000. The basic energy requirements of the Reference Energy Systems (3) were used for these analyses. The range over which the partition could vary was determined by varying the quantity of petroleum that was available and forcing the substitution of electric power generated in coal-

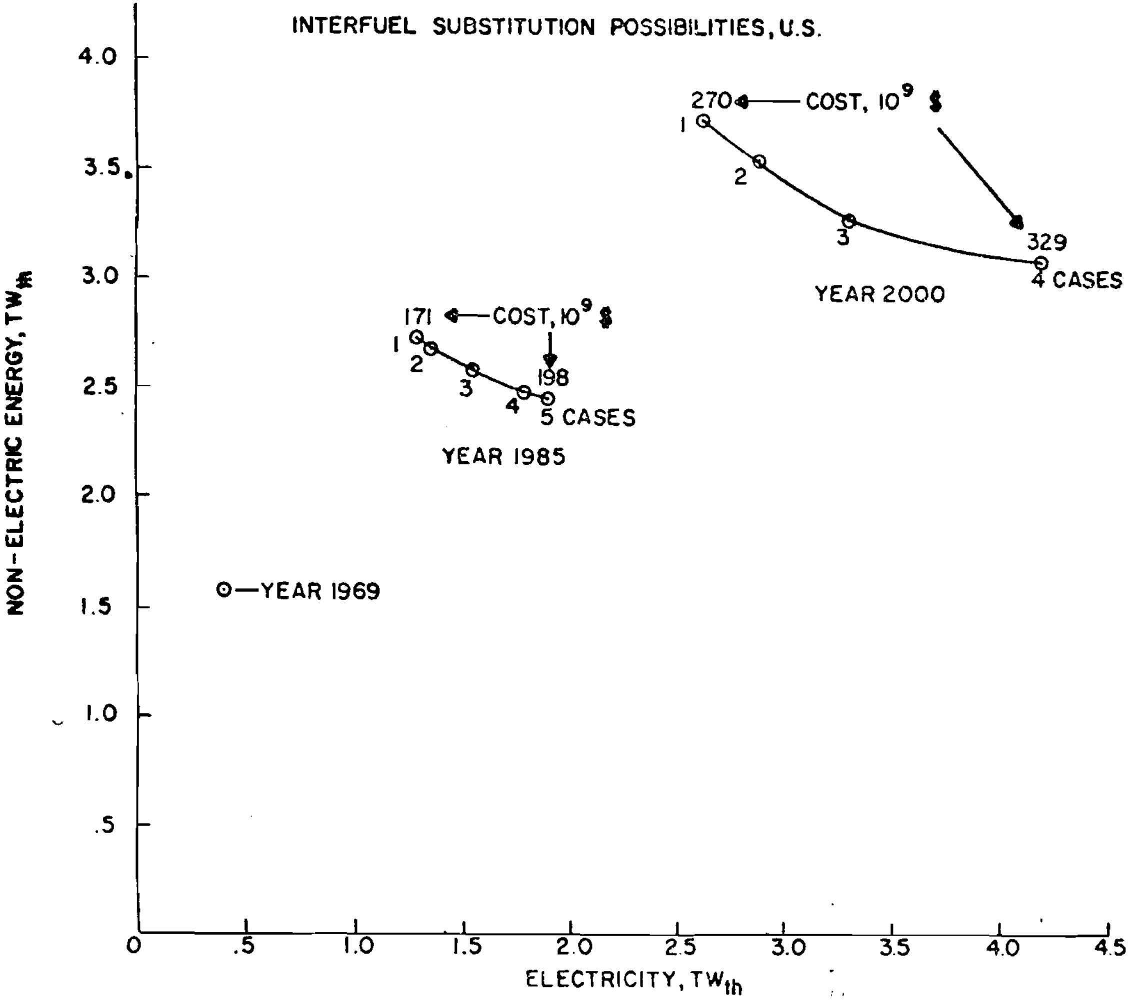
fired and nuclear power plants. These substitutions are of particular interest because of their relevance to increased self-sufficiency. The minimum electrification case in each study year corresponded to the allowance of unlimited oil imports.

The new technologies that are considered in this series of analyses are

-- hydrogen produced electrolytically with off-peak power
-- fuel cells for peaking use, and
-- electric automobiles for limited urban use.

Limited implementation of coal gasification was allowed in both 1985 and 2000; however, coal liquefaction technology was excluded. This technology would provide an alternative source of liquid fuels to the transportation sector and would allow the minimum electrification cases to be attained with lower levels of oil imports.

The range over which the partition of the energy system may vary is illustrated in Figure 2 where the resource consumption for electric generation is plotted against the resource consumption for non-electric users, both in units of annual terrawatts thermal (TW_{th}) where 1 TW-year = 29.9 x 10^{15} Btu. The partition for 1969, when 21.7% of the energy resources were consumed for electric generation, is given for reference



PARTITION OF ENERGY SYSTEM, 1985 AND 2000

FIGURE 2

purposes. It may be seen that for 1985 the partition may range from 31.7% resources consumption for the electric sector up to 43.1%, while in the year 2000 the range is 41.5% to 57.5%. Thus, even the minimum electrification cases for those years indicate continued growth of the electric sector at a more rapid rate than the non-electric sector.

The range of variability increases for the year 2000, of course, due to the longer lead time available for such fundamental shifts to occur. The minimum electrification case in each period is based on the availability of unlimited quantities of imported oil. As the oil supply is constrained, forcing increased electrification, the cost increases and the total resource consumption increases. Specific cases considered are represented by the data on the curves and the substitutions and new technologies involved in each case are discussed below. The cost, resource consumption, and emissions corresponding to each case for 1985 and 2000 are given in Tables I through IV.

It must be pointed out that the version of the linear programming model used in this analysis did not incorporate supply or demand elasticities. Other fuels may be substituted at different efficiencies as relative prices change. The total resource consumption can vary but the basic energy demand to be satisfied (e.g., number of passenger miles of automobile and aircraft travel, square feet of living space to be heated and cooled) remains the same. One would expect some changes in these parameters due to substitution of other activities as prices change. Although such changes are not considered in the model, consideration of the changes in the marginal cost of serving specific demand sectors would indicate where changes in the level of basic energy demand would be greatest. Table V and VI indicate, for the years 1985 and 2000 respectively, the changes in marginal cost for each demand sector relative to the cost in the minimum electrification case. Examination of Table V indicates, for example, that the cost of input energy will change most drastically for the petrochemical and air transport demand sectors. Further analysis of the impact of these cost changes on the cost of and, in turn, on the demand for the product and service is required. These effects may be represented by a demand elasticity, which will be incorporated in a future version of the model.

The detailed results of the analyses and the assumptions made are discussed in the following sections.

YEAR 1985 ANALYSIS

Coal and nuclear fuel were preferred for base and intermediate load service in the 1985 runs; however, some oil (5.15×10^{15} Btu) and gas (3.45×10^{15} Btu) use for central station electric generation was specified exogenously. This specification is based on environmental considerations which will dictate the use of these clean fuels in some urban areas in plants that are in operation now and would not be retired prematurely.

Off-peak uses of electrical energy were constrained to the point that at least half the peak power demand had to be met with peaking devices such as gas turbines, pumped storage and hydrogen fuel cells. The latter two concepts used off-peak power, as did the electric car, which was introduced to a limited extent in all the 1985 runs. The LWR constraint was set at 15.0×10^{15} Btu input and coal steam electric capacity was taken to be the marginal supplier. Total coal use was constrained at a very high level, 1800×10^{6} tons; however, no more than 1500×10^{6} tons was used in any case. Coal could be burned directly for process heat to satisfy up to about twenty percent of that energy demand, could be converted to electricity, or could be gasified to contribute up to about seven percent of total methane supply. The natural gas constraint was set at 28.39×10^{15} Btu. Oil was supplied at five different levels, corresponding to the five 1985 cases: 50.8×10^{15} Btu, 47.1×10^{15} Btu, 44.1×10^{15} Btu and 43.1×10^{15} Btu.

The new technologies and substitutions considered in this series of runs were: the hydrogen fuel cell for peaking and hydrogen used directly for space heat, water heat and process heat, the hydrogen being produced with off-peak electricity; increased electrification of process heat and space heat; alternate fuels including methane and electrolytic hydrogen for transportation; and limited implementation of the electric car (4% of automotive travel).

The general substitution trend in this series of runs involves the increased electrification of space heat and process heat, and the replacement of oil fired gas turbines with hydrogen fuel cell peaking devices. As the oil supply is further constrained, some methane is substituted for oil in the transportation sector with the methane that is shifted to this sector being replaced by electricity generated from coal. Coal liquefaction technology was not considered in this analysis, but would provide an alternative path to this latter indirect substitution of coal for oil.

Following is a detailed summary of the 1985 runs. Implementation levels of substitution on new technologies are indicated as the fraction of the basic energy that they satisfy in given demand categories. The basic energy demand corresponds to the amount of energy required to perform an activity, such as automotive transport and space heat, assuming that the energy could be used at 100% efficiency. Alternative energy supply categories compete at different efficiencies to serve these demands in the optimization model.

Run 1: In this run peak power was supplied by gas turbines and hydroelectric plants. Process heat for industry was supplied solely from direct methane and coal burning. Electric resistance space heat was employed to the point at which the winter and summer peaks balanced. Water heating was done with off-peak electricity to the extent allowed, or about thirty-nine percent of that basic energy demand. Transportation demands were met solely with oil, except for the electric car, which came in at the maximum amount allowed, and electric rail demand.

Run 2: Pumped storage use increased to the allowed limit (69.2×10^9 kwh) and gas turbine use for peaking decreased. More space heating was done electrically resulting in a winter peak electric demand condition.

Run 3: The hydrogen fuel cell, charged with off-peak electricity, was used for electric peaking service. Gas turbines disappeared entirely from the optimal solution. Electricity supplied about seven percent of the process heat demand and a third of the space heat demand, the maximum level of substitution permitted in the latter end use.

Run 4: Use of the hydrogen fuel cell for peaking increased, as well as the use of electricity for process heat. Some methane was substituted for gasoline as an automotive fuel.

Run 5: There were further increases in the implementation of the hydrogen fuel cell (to 33% of demand) and the methane fueled automobile (to 27% of demand). Electricity supplied 24% of basic process heat demand.

YEAR 2000 ANALYSIS

In this series of analyses nuclear fuel was assumed to be the marginal resource for electric generation and coal was constrained in this use to 19.5×10^{15} Btu input. Light Water Reactor (LWR) capacity was unconstrained. The total coal constraint was set at 31.4×10^{15} Btu or about 1260 million tons. The natural gas constraint was 33.98×10^{15} Btu, and coal gasification could contribute another 6.9×10^{15} Btu. Oil was supplied at four different levels, starting with 71.38×10^{15} Btu and decreasing by 10.0×10^{15} Btu in each succeeding case. In Runs 1 through 4, implementation of the electric car was restricted to ten percent of basic automobile demand. In the fifth run its implementation was unlimited, but reallocation of the extra oil saved was not permitted.

Otherwise, substitutions and technologies were the same as for the 1985 run but were not limited in their implementation.

Run 1: In each run, the electric car met ten percent of basic automobile demand, and remaining transportation demands except electrified rail were satisfied with oil. Coal and gas were burned directly for process heat, and 1.77 x 10^{15} Btu of coal was gasified. Summer and winter peaks for space conditioning were balanced. Off-peak electricity met 47% of basic water heating demand. Peaking power came half from hydroelectric plants, half from gas turbines and pumped storage, with the latter two contributing equal shares.

Run 2: This run yielded the same results as the first, except that the percent of space heat demand satisfied by electricity grew from 22.6% to 47.1%, causing a winter peak electric demand condition.

Run 3: The overall load factor improved in this run as base-loaded LWR's served a combination of peak and off-peak electric demands. The remaining peaking power demand was supplied in roughly equal amounts from hydroelectric, pumped storage, and hydrogen fuel cells. The latter replaced gas turbines, which disappeared. Electricity met 88% of space heat demand.

Run 4: For the first time, process heat demand was met by electricity (11% of demand) and hydrogen (10% of demand).

All space heating was done electrically. Methane fueled automobiles appeared, and satisfied 69% of automobile demand. Run 5: The results were identical with those for Run 4. Making hydrogen for process heat demands with off-peak power was preferred to charging electric car batteries. Had reallocation of the oil saved been permitted, however, the results would have been different.

CONCLUSIONS

This analysis of electrification of the United States energy system raises a number of questions for further study. Technologies that became important with increased electrification include the fuel cell, electric car, and a synthetic fuel such as hydrogen that may be produced from off-peak power. The role of these technologies are demonstrated in the computer runs described in the previous sections. Other technologies that can be important in an electric intensive energy system. but that were not addressed in this analysis, include the heat pump for space heating and high efficiency induction heating for industrial processes.

The substitutions taking place in the more extreme electrification cases imply significant increases in the cost of service to several energy demand sectors that now rely heavily on liquid or gaseous general-purpose fuels. As a result of increased energy costs, certain products and services will be affected by the substitution of less energy intensive activities in the economy. This involves changes in life styles, and the analysis of such socio-economic change is beyond the scope of this analysis.

This study provides a preliminary review of some of the consequences of increased electrification of the energy system. The systems considered involved the use of coal and nuclear fission energy to generate increased amounts of electric power. Solar-electric, geothermal and fusion energy could be employed in later periods. Alternative future strategies that must be considered are the large scale conversion of coal to liquid and gaseous fuels and the large scale use of direct solar heat.

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TABLE I

COST AND RESOURCE CONSUMPTION, YEAR 1985

	Case				
	1	2	3	4	5
Cost, $\$10^9$	170.827	173.069	181.790	193.869	198.103
Electric Sector, TW					
Coal	0.271	0.360	0.585	0.829	0.912
Oil and Gas	0.287	0.287	0.287	0.287	0.287
LWR	0.500	0.500	0.500	0.500	0.500
LMFBR	0.	0.	0.	0.	0.
Hydroelectric	0.144	0.144	0.144	0.144	0.144
Geothermal	0.017	0.017	0.017	0.017	0.017
Total Energy Systems	0.003	0.003	0.003	0.003	0.003
Gas Turbines	0.051	0.019	0.	0.	0.
INPUTS	1.273	1.330	1.536	1.780	1.863
Non-Electric Sector, TW					
Oil and Gas	2.381	2.337	2.232	2.132	2.099
Coal	0.346	0.346	0.346	0.346	0.346
Solar	0.011	0.011	0.011	0.011	0.011
INPUTS	2.738	2.694	2.589	2.489	2.456
TOTAL INPUTS	4.011	4.024	4.125	4.269	4.319
Hydrogen Produced	0.	0.	0.009	0.012	0.013

1 Total oil at 53.1 x 10^{15} Btu
2 " " " 50.8 x 10^{15} "
3 " " " 47.1 x 10^{15} "
4 " " " 44.1 x 10^{15} "
5 " " " 43.1 x 10^{15} "

TABLE II

YEAR 1985

						CASE		
ENVIRONMENTAL EFFECTS				1	2	3	4	5
CNTRL	CO_2	10^{11}	LB	30.719	35.047	49.212	65.561	71.118
CNTRL	CO	10^9	LB	1.250	0.767	0.701	0.993	1.093
CNTRL	NO_x	10^9	LB	9.009	10.665	15.472	20.870	22.704
CNTRL	SO_2	10^9	LB	14.463	17.256	25.116	33.877	36.854
CNTRL	PART	10^9	LB	4.375	5.684	9.042	12.692	13.933
CNTRL	HC	10^9	LB	0.391	0.305	0.320	0.408	0.439
CNTRL	RAD	10^3	CU FT	16.727	16.727	16.727	16.727	16.727
CNTRL	HEAT	10^{15}	BTU	38.091	39.748	45.917	53.217	55.698
DCNTR	CO_2	10^{11}	LB	111.577	109.539	104.683	101.155	100.046
DCNTR	CO	10^9	LB	79.747	79.721	79.689	79.685	79.685
DCNTR	NO_x	10^9	LB	30.588	30.384	29.820	29.522	29.441
DCNTR	SO_2	10^9	LB	15.426	14.694	12.952	12.697	12.697
DCNTR	PART	10^9	LB	19.658	19.554	19.307	19.232	19.216
DCNTR	HC	10^9	LB	18.397	18.372	18.263	18.153	18.117
DCNTR	RAD	10^3	CU FT	0.000	0.000	0.000	0.000	0.000
DCNTR	HEAT	10^{15}	BTU	82.056	80.737	77.595	74.595	73.595
TOTAL	CO_2	10^{11}	LB	142.297	144.585	153.895	166.717	171.164
TOTAL	CO	10^9	LB	80.998	80.488	80.390	80.679	80.778
TOTAL	NO_x	10^9	LB	39.598	41.050	45.291	50.392	52.145
TOTAL	SO_2	10^9	LB	29.889	31.950	38.068	46.574	49.551
TOTAL	PART	10^9	LB	24.033	25.238	28.349	31.924	33.149
TOTAL	HC	10^9	LB	18.788	18.678	18.583	18.561	18.556
TOTAL	RAD	10^3	LB	16.727	16.727	16.727	16.727	16.727
TOTAL	HEAT	10^{15}	BTU	120.148	120.485	123.512	127.813	129.294

(Continued...)

Table II, Year 1985

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ENVIRONMENTAL EFFECTS	1	2	3	4	5
LAND USE, 10^3 SQ MI					
STRIP MINING	0.194	0.222	0.293	0.369	0.395
COAL FIRED ELEC.	0.283	0.375	0.609	0.863	0.949
OIL FIRED ELEC.	0.041	0.041	0.041	0.041	0.041
GAS FIRED ELEC.	0.018	0.018	0.018	0.018	0.018
NUCLEAR	0.112	0.112	0.112	0.112	0.112
ELEC. TRANSMISSION	13.385	13.977	15.763	18.119	18.920
ELEC. SECTOR INPUTS, 10^{15} BTU	38.191	39.848	46.017	53.317	55.798
NON-ELEC. INPUTS, 10^{15} BTU	81.956	80.637	77.495	74.495	73.495

TABLE III

COST AND RESOURCE CONSUMPTION, YEAR 2000

	CASE				
	1	2	3	4	5
Cost, $\$10^9$	270.197	277.731	294.772	329.240	329.240
Electric Sector, TW					
Coal	0.652	0.652	0.652	0.652	0.652
Oil and Gas	0.	0.	0.	0.	0.
LWR	1.699	1.931	2.401	3.320	3.320
LMFBR	0.	0.	0.	0.	0.
Hydroelectric	0.199	0.199	0.199	0.199	0.199
Geothermal	0.033	0.033	0.033	0.033	0.033
Total Energy Systems	0.003	0.	0.	0.	0.
Gas Turbines	0.054	0.054	0.	0.	0.
INPUTS	2.640	2.869	3.285	4.204	4.204
Non-Electric Sector, TW					
Oil and Gas	3.306	3.128	2.853	2.519	2.519
Coal	0.396	0.396	0.396	0.396	0.396
Solar	0.015	0.015	0.015	0.015	0.015
INPUTS	3.717	3.539	3.264	2.930	2.930
TOTAL INPUTS	6.357	6.408	6.549	7.134	7.134
Hydrogen Produced	0.	0.	0.020	0.131	0.131

	Max. Oil	Electric Car Implementation
1	71.38	10%
2	61.38	10%
3	51.38	10%
4	41.38	10%
5	41.38	Unlimited

TABLE IV

YEAR 2000

						CASE		
ENVIRONMENTAL EFFECTS				1	2	3	4	5
CNTRL	CO_2	10^{11}	LB	46.277	46.293	43.668	43.668	43.668
CNTRL	CO	10^9	LB	1.752	1.758	0.780	0.780	0.780
CNTRL	NO_x	10^9	LB	14.904	14.907	14.418	14.418	14.418
CNTRL	SO_2	10^9	LB	24.016	24.020	23.400	23.400	23.400
CNTRL	PART	10^9	LB	9.766	9.766	9.750	9.750	9.750
CNTRL	HC	10^9	LB	0.431	0.432	0.236	0.236	0.236
CNTRL	RAD	10^3	CU FT	56.678	64.426	80.116	110.781	110.781
CNTRL	HEAT	10^{15}	BTU	78.896	85.854	98.293	125.792	125.792
DCNTR	CO_2	10^{11}	LB	152.405	144.145	131.210	120.598	120.598
DCNTR	CO	10^9	LB	55.049	62.717	65.863	49.349	49.349
DCNTR	NO_x	10^9	LB	41.365	41.215	40.225	37.911	37.911
DCNTR	SO_2	10^9	LB	22.735	19.867	15.226	15.835	15.835
DCNTR	PART	10^9	LB	25.101	24.690	24.033	23.940	23.940
DCNTR	HC	10^9	LB	17.156	17.895	18.090	16.050	16.050
DCNTR	RAD	10^3	CU FT	0.000	0.000	0.000	0.000	0.000
DCNTR	HEAT	10^{15}	BTU	111.298	106.026	98.446	92.860	92.860
TOTAL	CO_2	10^{11}	LB	198.683	190.438	174.878	164.267	164.267
TOTAL	CO	10^9	LB	56.802	64.475	66.643	50.129	50.129
TOTAL	NO_x	10^9	LB	56.269	56.123	54.643	52.329	52.329
TOTAL	SO_2	10^9	LB	46.751	43.887	38.626	39.235	39.235
TOTAL	PART	10^9	LB	34.868	34.456	33.783	33.690	33.690
TOTAL	HC	10^9	LB	17.587	18.327	18.327	16.286	16.286
TOTAL	RAD	10^3	LB	56.678	64.426	80.116	110.781	110.781
TOTAL	HEAT	10^{15}	BTU	190.194	191.880	196.739	218.652	218.652

(Continued...)

Table IV, Year 2000

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ENVIRONMENTAL EFFECTS	1	2	3	4	5
LAND USE, 10^3 SQ MI					
STRIP MINING	0.329	0.329	0.329	0.329	0.329
COAL FIRED ELEC.	0.679	0.679	0.679	0.679	0.679
OIL FIRED ELEC.	0.000	0.000	0.000	0.000	0.000
GAS FIRED ELEC.	0.000	0.000	0.000	0.000	0.000
NUCLEAR	0.381	0.433	0.539	0.745	0.745
ELEC. TRANSMISSION	27.439	29.737	34.178	43.578	43.578
ELEC. SECTOR INPUTS, 10^{15} BTU	78.996	85.854	98.293	125.792	215.792
NON-ELEC. INPUTS, 10^{15} BTU	111.198	106.026	98.446	92.860	92.860

TABLE V

RELATIVE CHANGE IN MARGINAL COST OF DEMAND, 1985

	Multiple of Case 1 Marginal Cost			
Case	2	3	4	5
Demand Category				
Misc. Electric Base Load	1.03	1.04	1.04	1.04
Misc. Electric Intend Load	1.04	1.05	1.05	1.05
Process Heat	2.18	3.15	3.15	3.15
Ore Reduction	1.00	1.00	1.00	1.00
Petrochemicals	2.42	3.60	4.65	4.65
Space Heat	1.85	2.56	2.56	2.56
Air Conditioning	0.67	0.68	0.68	0.68
Water Heat	1.85	2.56	3.32	3.32
Air Transport	1.95	2.73	3.57	3.57
Truck, Bus	1.70	2.28	2.91	2.91
Rail	1.04	1.05	1.05	1.05
Automobile	1.70	2.28	2.91	2.91

TABLE VI

RELATIVE CHANGE IN MARGINAL COST OF DEMAND

YEAR 2000

DEMAND CATEGORY	Multiple of Case 1 Marginal Cost 2	 3	 4	 5
Misc. Elec. Base Load	1.04	1.04	1.04	1.04
Misc. Elec. Int. Load	1.06	1.06	1.05	1.05
Process Heat	2.33	2.33	3.05	3.05
Ore Reduction	3.89	3.89	5.45	5.45
Petrochemicals	2.64	3.57	4.63	4.63
Space Heat	1.71	1.94	1.94	1.94
Air Conditioning	0.70	0.62	0.61	0.61
Water Heat	1.94	2.59	3.22	3.22
Air Transport	2.05	2.77	3.48	3.48
Truck, Bus	1.76	2.29	2.80	2.80
Rail	1.06	1.06	1.05	1.05
Automobile	1.76	2.29	2.80	2.80

Discussion

Mr. Janin (France) first commented that figure 2 shows that the substitution efficiency between electricity and other energy forms must be far away from one. But if one takes into account e.g the increasing oil price on the one hand and the more efficient electrical systems--for example space heating systems--on the other hand, this gives rise to doubt. He also stressed that in the case of process heat, the substitution efficiency should be very close to one because in the industrial process heat sector, one is going to change from steam or boiling water to other new technologies, for example, osmosis. Finally, he asked what kind of costs are considered in the model.

Mr. Hoffman first replied to the comment and remarked that they have a good basis to calculate or estimate the efficiency of substitutions. He agreed in the case of space heating, but he disagreed in the case of process heating. He noted that they are thinking more in terms of increased utilization and induction heating techniques rather than in convective and conductive process heating, and there are efficiency increases to be gained in those industries which can make effective use of induction heating. Since the industrial process heat sector is a very large one, they would like to try to distinguish in industrial process heat between direct heat requirements as a function of temperature, and the lower process heat requirements which can be satisfied conveniently by power plants using back pressure turbines; and to introduce this in the model as a first cut. Then they would like to look further at the amount of heat that could be switched over to induction heating which can be done very efficiently via electricity. But they do not know other processes which are considerably more efficient. Then, with regard to the question about the cost, he remarked that the cost coefficients in the objective function include the fuel cost, the operative cost and an amortized capital cost--the capital cost is amortized in a fixed charge rate of something like 15%. The cost coefficient does not include the cost of the utilizing device but they are still developing cost data on utilizing devices and they will use them in the future.

Another participant then had a question on tables 1 and 3. He asked if the hydrogen technology will be ready in 1985 because it seemed to him from table 1 and 3 that the gas turbine is substituted just at the time the hydrogen comes in. Mr. Hoffman replied that it was not the complete replacement of gas turbines by fuel cells; there were 2 or 3 technologies that were replacing the gas turbine. He did not know about the fuel cell but he noted that there are some experts and they are confident that the fuel cell will be successful in 1978-1979.

Mr. Styrikovich (USSR) asked if the fuel cell will also be cheap enough for big loads to come into the market. Mr. Hoffman said yes and remarked that they are using an optimistic estimate and that comes out for fuel cell components something like $150/kW.

Mr. Krymm (IAEA)asked on what basis the demand projection for the different sectors is done. Mr. Hoffman replied that this is done in the residential area on the basis of the projected number of households. They project the number of house-holds expected to the year 2000 and, given a level, they make some decision that will then be some mix of multi-family and single-family dwellings. For this study they assumed there would be the same mixture that they have in the USA now. Projection on increased use of insulation in these homes in response to conservation requirements--there are standards now being written--are all in the energy requirements for space heating, and it is really defined as the amount of heat (number of Btu's) leaking through the walls of the house. The model calculates that using the utilization efficiency. In transportation projections they were fortunate enough to have the help of the Department of Transportation in the USA which gave them projections of automobile and aircraft. In respect of projections for the purpose of technology assessment, they wished to use a conservative projection. So they wanted to plan for what they thought would be close to the maximum level of demand growth. This is a very special type of projection: it is not a forecast or prediction, it is a projection developed for new technologies. They felt that this is the appropriate type of planning projection to use for R & D assessment to new technologies because, if it turns out that the main levels do not reach the maximum demand level, then one does not need the technologies to the extent required. This seems to be suitable because benefit ratio and technology will not be as great as they initially calculated, but for the purpose of assessing the technologies it seemed to them to be an improvement.

A Concept for Evaluation of Timing of Transition into a Non-Fossil Energy Economy

Mitsuo Takei

I have been assigned the topic of timing of transition into a non-fossil energy economy, but I have had no experience with a comprehensive systems study of such a topic, and I hope that you will kindly bear with me if I fall short of a complete treatment of this matter.

At the Institute we are conducting, although within a limited range, two systems studies which have bearing on this theme. One is being presented under the title "A Model for Evaluation of the Growth of Nuclear Power in Future Power Systems,"[1] an evaluation of timing substitution or transition from conventional thermal power to nuclear power among the various sources in the future power system.

This model calculates the optimum distribution of thermal power (three types) and nuclear power (LWR, ATP, and FBR) to minimize system costs, with the annual marginal increase capacity taken as a premise following the annual load duration curve. In other words, in this model the substitution or transition between thermal power and nuclear power is realized through competition in respective generation costs. Further, data on the relative costs of each power source are given by the trend of construction costs and operation costs over a long-term period.

The second systems study is a model that forecasts long-term energy demand levels through consideration of the type of limitations which will be placed on the growth of the Japanese economy by the conditions of future energy supply.[2]

This model is divided into three sub-systems: i) the economic sector; ii) the energy sector; and iii) the environmental sector. The relationships among the sectors are computed by means of the system dynamics method.

In the first sub-system, the annual rate of increase in private capital investment is given (as an exogenous variable), and the components of the GNP are derived by econometric methods. Next, using the distribution r-- table given by the Input/Output table, distribution is simulated for final demand by each industrial sector. Then, using the inverse

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[1] A Model for Evaluation of the Growth of Nuclear Power in Future Power Systems.

[2] A Model for Assessing Long-Term Energy Demand.

matrix, levels of energy consumption are further derived from the value of production for each industrial sector. It can be said that, since the GNP distribution rate and the energy input coefficient of each industrial sector are variable, this model can be fully applied to the causes of future change in the Japanese economy.

In the second sub-system, the data on total energy demand derived in the first sub-model are distributed between petroleum and substitute fuels, and petroleum consumption is limited in accordance with the available amount of future supply conditions.

In the third sub-system, sulfur exhaust from the above volume of petroleum consumption is calculated to determine the amount of investment in desulfurization equipment necessary to make this sulfur exhaust correspond to environmental standards.

In this model, changes in the composition of future energy demand are sought based on changes in the macroscopic framework of the economy and in the industrial structure of Japan. But, on the other hand, this model does not carry out any particularly detailed study of the composition of energy supply other than setting, as an upper limit, the amount of oil supply which may be available to Japan as derived in another model.[3]

Regarding conversion of primary energy supply, we are already experiencing two historical realities. One is the typical conversion from coal to oil which has been taking place since the second half of the 1950's. During the worldwide surplus in petroleum supply, the domestic demand for coal (excluding coking coal) was reduced and later, the addition of restrictions by environmental standards resulted in a constriction of domestic production. The proportion of domestic coal (including coking coal) in the supply of primary energy fell from 45% in 1955 to 34% in 1960 and to 19% in 1965. We can interpret this type of conversion as a process of displacement of coal through market competition from petroleum, which is advantageous in terms both of price and utilization.

The other historical reality is the large-scale introduction of nuclear power sources which began during the early 1960's in America. The powerful American nuclear power industry built up the new market by the accumulation of technological development during the decade of the 1950's, and just at that time it took advantage of the continuing high level of demand for power plants. There is a large variety of fuels in America, as well as wide regional variation in fuel costs, and this undeniably was of benefit to the market strategy of the nuclear power industry. This American experience has extended to the industrial countries of Europe and to Japan, where there is now a secondary

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[3] A Model for the Simulation of the Future Oil Flow.

energy conversion under way. At the same time, this secondary conversion can be seen as a change in the conditions of energy supply from resources to technology, pointing out the long-term future trend.

The energy transition with which we are dealing here, however, holds broader problems and longer-range factors than the above two cases, and many points involved in the transition period should rather be understood as relating to the concepts of long-term energy strategy.

Beginning with the opening of the 1970's, the changes in the structure of world oil supply, which accelerated in particular following 1973, were a prime factor leading to the present situation, now called the oil crisis. For example, in Japan's case, the energy supply available through domestic sources in the year 2000 will not exceed 40% of the energy demand as extrapolated from present conditions, and should petroleum supplies be limited to available supplies during 1980-85, it is forecast that approximately 30% of the energy demand will not be met.

On the other hand, the level of long-term energy demand will be regulated by the nature of future economic and social development, and the composition of energy demand will be determined in response to changes in the forms predicted for final consumption. For Japan, the industrial sector accounts for 50% of all energy consumption. As such, it has become possible for controls on energy consumption to change the structure of industry, reorganizing the high energy consuming industry. At the same time, however, there still remain factors leading to major increases in per capita consumption in household sector, which now stands at one-fifth of the American level and at half the level of the countries of Europe, and there is also much room for improvement in the form of that consumption.

Considering such forecasts, we can see that the gap in long-term energy demand and supply should not be thought of as a mere shortage of supply to meet the demand; in many ways it should be interpreted as a lack of adequate means to deal with qualitative requirements of energy consumption. Optimal choice of energy consumption, and rationalization of energy transportation, improvement of environmental conditions, and other factors deriving from the form taken by final consumption are unignorable factors pushing forward the transition from fossil energy to non-fossil energy.

When looked at in this way, the study of what measures can be adopted to close the forecasted gap in energy demand and supply can be considered as the formulation of long-term energy strategy. For a high energy consuming country such as

Japan, that energy strategy can be understood as a process of policy selection for the integration of the energy supply, the environment, and the national economy, at the same time fitting the strategy of the goals of stabilization and optimization of the world energy supply. The expansion of the supply of non-fossil energy resources is a preferred option for industrial countries to achieving simultaneously optimum distribution of the world's energy resources and establishment of domestic self-sufficiency.

We can see in Figure 1 that a concept can be formulated for the estimation of the gap between energy supply/demand, and within the area of this concept we shall be able to make a calculation model.

For this discussion, the level of energy demand and composition of supply in 2000 in Japan can be forecasted as shown in Figure 2, and the three types of potential gaps are estimated in terms of amount. These gaps convert to actual gaps, which are indicated in terms of energy supply.

As mentioned above, the choice of measures to close this gap is mainly subject to political decision. These measures include both economical and technological methods. In the area of economical method, we can control the level of energy demand by the exercising of economic policy. In the area of technological method, we can present alternative energy sources from nuclear power, reutilization of fossil resources and renewable energy to fusion. Of these, only nuclear power is dealt within systems studies, and it is called reactor strategy.

Technological choices to satisfy the energy gap are affected by many techno-economic factors. These factors can include:

Lead-time for development and supply

R & D investment

Probability of supply

Assessment of environmental effect both in production and final use

Cost, production and transportation

Form of supply

Limiting factor set by each energy

Minimizing environmental effect in whole energy supply/consumption system.

Fig. 1 Concept of Energy Supply/Demand Model

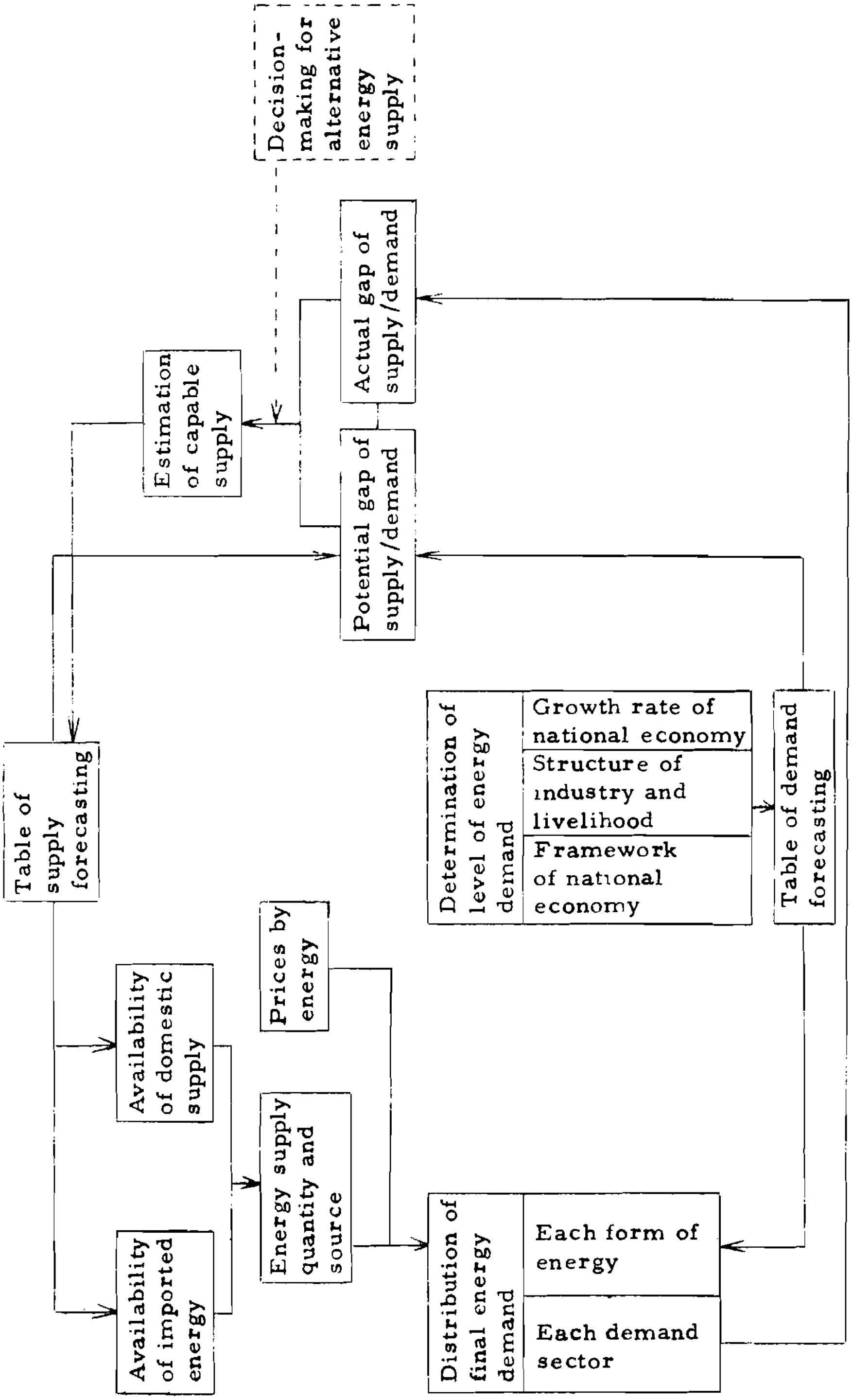
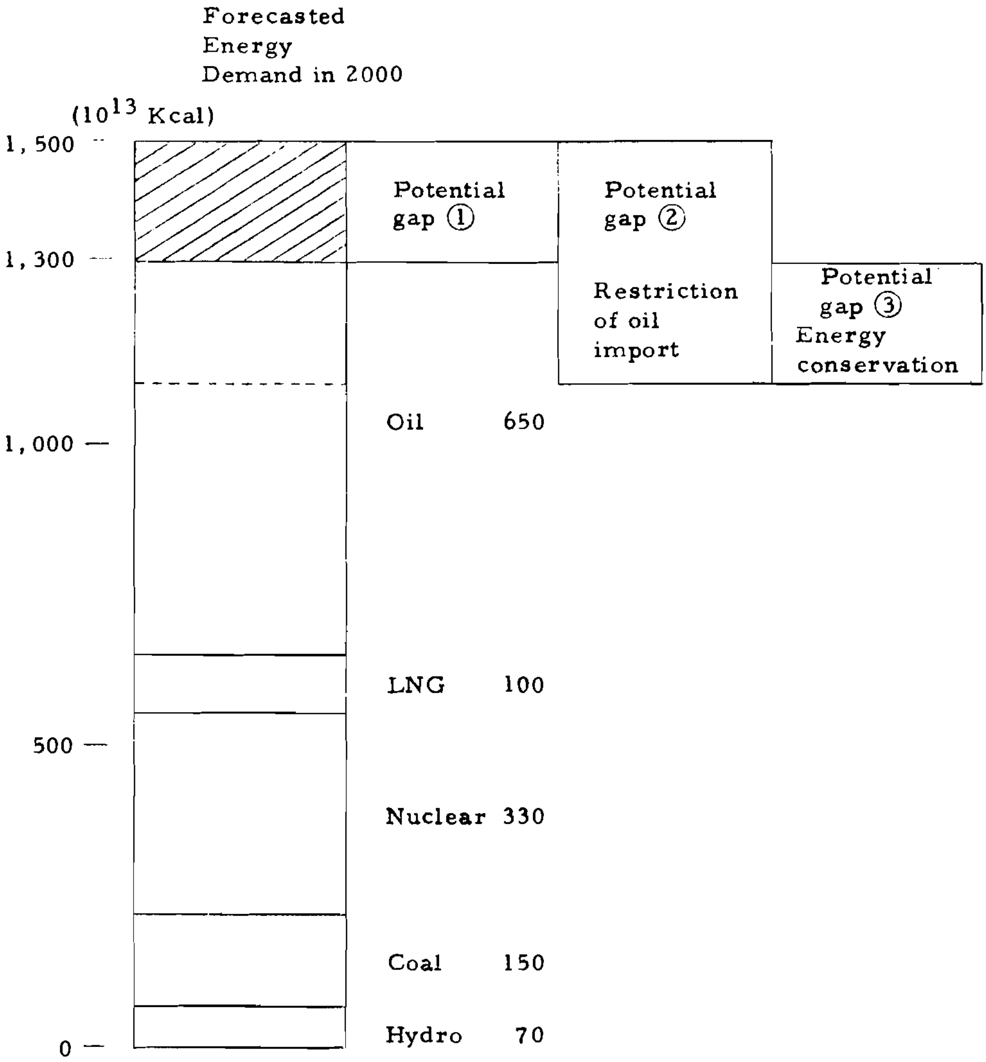
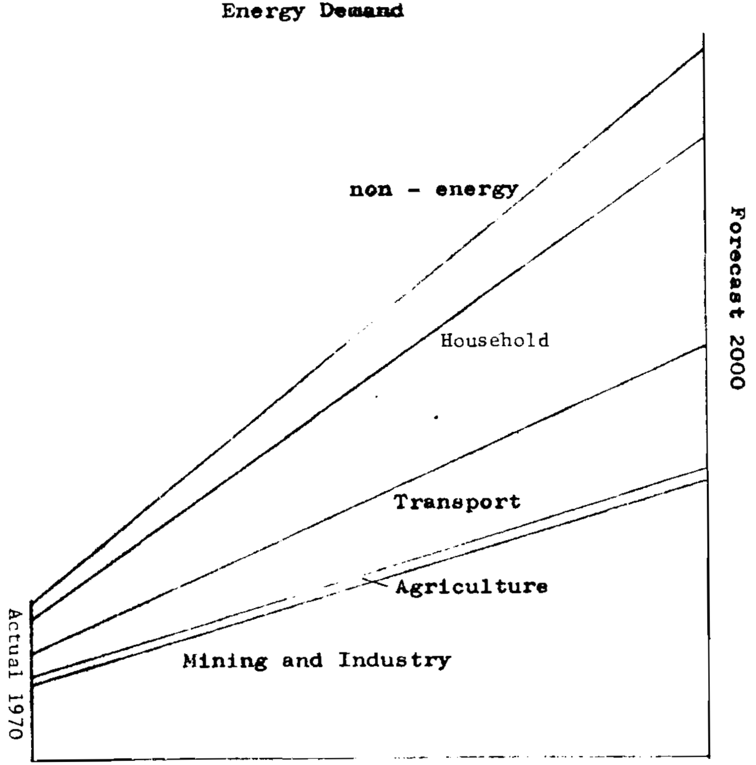
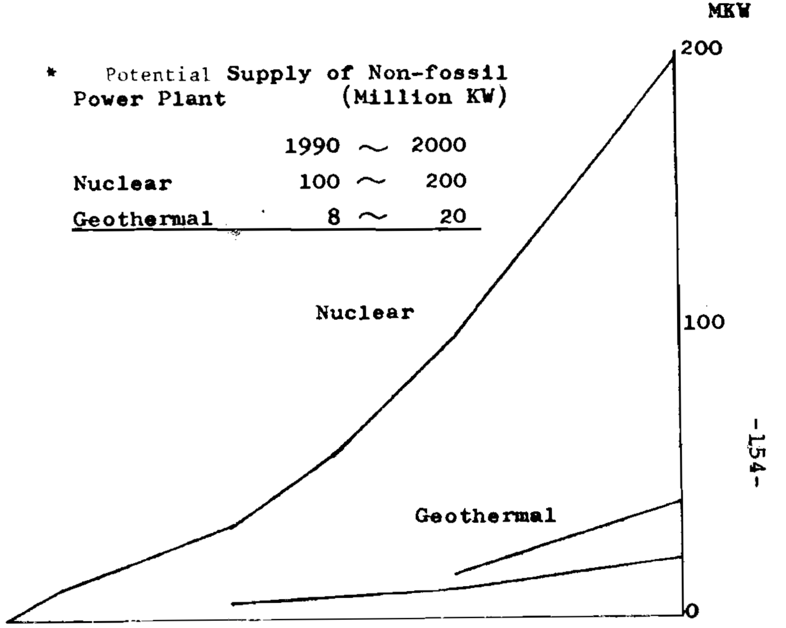


Fig. 2


Forecasted
Energy
Demand in 2000
(10^{13} Kcal)
1,500
1,300
1,000
500
0
Potential gap ①
Potential gap ②
Restriction of oil import
Potential gap ③
Energy conservation
Oil 650
LNG 100
Nuclear 330
Coal 150
Hydro 70

APPENDIX 1



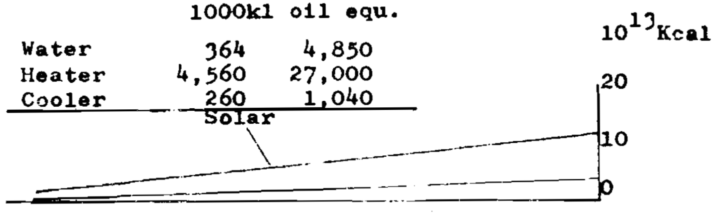


* Potential Supply of Non-fossil Power Plant (Million KW)

	1990	~	2000
Nuclear	100	~	200
Geothermal	8	~	20

* Potential Supply of Solar Energy in Household Use

	1000kl oil equ.	
Water	364	4,850
Heater	4,560	27,000
Cooler	260	1,040



APPENDIX 2

1. Composition of Energy Demand (%)

Sector	1970	2000
Mining, Industry	56	44
Transport	13	17
Agriculture	2	1
Household	18	28
Non-Energy	11	10
Total	100	100

2. Capacity of Power Generating (1970 ~ 2000)

	1970	(%)	1980	(%)	2000	(%)
Total demand of power (10^9 kwh)	320		737		1,874	
power-generation (")	358	(100)	810	(100)	2,061	(100)
Nuclear power (")	5	(1)	210	(26)	1,200~1,300	(58~63)
Hydro-power (")	78	(22)	104	(13)	190	(9)
Thermal-power (")	275	(77)	496	(61)	671~571	(33~28)
Capacity of power generation	68	(100)	150	(100)	361 ~365	(100)
Nuclear-power (10^6kw)	1	(2)	32	(21)	180 ~ 200	(50~55)
Hydro-power(")	20	(29)	37	(25)	71	(20)
Thermal-power (")	47	(69)	81	(54)	110 94	(30~26)

Discussion

Mr. Häfele (IIASA) asked whether they consider the growth of demand and whether they use a limitation for the future demand or a continuously increasing demand. Mr. Takei replied that they have another model to calculate the development of the structure of the economy and the industry, and that they use this model to determine the future demand.

Mr. Janin (France) then commented that they have very similar problems and also similar solutions. They use nuclear power to a great extent; thus they are planning to have 75% of electricity by nuclear power plants in 1985 and it should be in the same order of magnitude in the year 2000. Furthermore, he asked if a real constraint exists which levels down the nuclear power to 60% of the electricity demand as shown in appendix 2. Mr. Takei replied that they have different problems in the promotion of nuclear power which have not been solved and that is why he does not think they would have more than 60%.

Mr. Manne (IIASA) asked about the small scale residential and commercial use of solar energy and how far away this technology is from implementation with "Project Sunshine". Mr. Takei wanted Mr. Mori (Japan) to answer. Mr. Mori replied that they plan to have solar power generation on a large scale at the end of this century, and on a small scale, which means house heating and cooling, in 7-8 years. But this is very much the beginning, and also "Project Sunshine" is just at the beginning--this actually began through the ideas of some people from the universities.

Progress Report on a Review of Energy Models Developed in Various Countries

J.-P. Charpentier

The paper "Progress Report on a Review of Energy Models Developed in Various Countries" is not reproduced here, but is available as a separate document from the International Institute for Applied Systems Analysis. Its publication listing is: "A Review of Energy Models: No. 1- May 1974," RR-74-10, July 1974.

Discussion

One participant made the comment that he is extremely worried about most of the energy models. They give the impression of representing reality which can be treated by rational methods. The crucial point especially is that the decisior makers get the wrong impression, while the model makers are more aware of the problems. The model makers appear to represent a nearly closed system, but the only system which can be assumed to be closed is the atmosphere, and within that are the ecosphere, the sociosphere, etc. The only variable that actually considers the linkage between the energy system and the sociosphere is the demand variable, and this is very often pushed up by advertising, the artificially shortened life time of products, low quality, etc. Therefore, he suggested treating the demand variable as an exogeneous variable that is independent of the supply.

Then, another delegate asked whether it would be possible to include the availability of the models in that paper. Mr. Häfele agreed, and replied that the availability was one of the problems in deciding which model should or should not be included in that paper. Therefore, they decided on a more pragmatic basis to include only those models which are reported in the unclassified literature in somewhat greater detail. They did not draw the distinction line between completely available and unavailable because they felt that it would not be fully relevant if only the entirely available models are included. Thus, it seems now that one has to contact the author or the ministry, etc., if one wants to get more details.

Another participant, however, wanted to carry the point a little further. He remarked that ultimately some models that are of interest do not exist even in the form of detailed reports but only in the form of computer programs. In this case it would be of great interest, particularly in comparing models for their compatibility of assumptions and output, if some efforts were made by groups such as IIASA--even on a small scale--to make these computer programs on a comparable basis available for use in various institutions. Mr. Häfele replied that he thought he knew what this participant was referring to, because they are both in the reactor field and there are now sophisticated data banks for nuclear data and reactor codes. But he did not think that now is the right time to make a similar effort in the modelling field, that it could be done in 5 years perhaps. Then he noted that on the other hand, if he looks at the amount of effort that has to go into it to make it operational, he must say that IIASA is not staffed for that obligation; and he asked Mr. Raiffa for his opinion on that point. Mr. Raiffa commented that a series of symposia has been started on problems of global modelling. A few weeks ago the first of these took place at IIASA, with Profs. Pestel and Mesarovic discussing their global model; this will be followed by other global modelling efforts, and in all cases they would ask for the computer programs to be brought to IIASA and to be worked over. These programs thus become available to those who want to play with the models. This may involve 5 to 6, or at the outside 10, such modelling efforts. If in the area of energy modelling IIASA took on all computer programs, it might be swamped. Mr. Raiffa thought it desirable to take a few of the more common ones and try to bring the software to IIASA.

New Ways and New Possibilities of Modelling the Electric Power System Development

Imrich Lencz

A mathematical model became a means of solving the problems of the development of large and complex technical and economical systems. In the Power Research Institute of Czechoslovakia the so-called Multimodel has been prepared for solving the problems of the electric power system development. The Multimodel is an effective and a complex model system based on using an automated data base and controlled by instructions of a special problem-orientated communication language. It substantially increases the effectiveness of model studies in the field of analysis and synthesis of the development of present-day electric power systems.

The Multimodel results from the application of ideas and approaches of the applied systems analysis.

1. A modelled system

The structure of the modelled system, i.e. of the electric power system and its environment, is objectively described in Fig.1.

It is composed of subsystems of several types of power plants (conventional and special thermal power plants, nuclear power plants, storage hydro plants and pumped hydro plants), of the subsystem of electricity transmission, as well as of that of electricity consumption.

It has important relationships to some environmental subsystems (the subsystem of fuel supply, the subsystem of the complex use of water resources, subsystems of centralized heat supply) and to the electric power systems of other countries.

2. Technical realization of the system model - the Multimodel of the electric power system

An effective means of modelling the system under consideration is the system of models called the Multimodel of the electric power system. The principle of its technical realization is to be seen in Fig.2.

The Multimodel is based on using an automated data base in which all the fundamental technical and economical information is concentrated, describing the initial stage and the conditions of the modelled system development, including the prognosis of the development of subsystems of its environment. All the data stored in the base are divided into effectively chosen data files.

The modelled system is described in the Multimodel by several models basing on a common set of initial premises which regard the same system (eventually its subsystems) from several different but mutually completing points of view. The model system as a whole is an isomorphic description of the modelled system. The common mathematical and logical formulation of the systemmodels is stored in the external memory of the computer as a number of specialized algorithms.

The models of the Multimodel produce new information which is stored in the form of data files in the results base of the Multimodel.

The solving of partial or complex problems of the development of the electric power system is based on model experimontations.

A necessary communication is secured between the models of the Multimodel and between the model system and the environment (the modeller). For the management of this communication a special high-level problem-orientated language called EMS (Energy System Modelling) has been elaborated. Its instructions are of three types:

- input instructions enable the chosen data files required for the operation of a particular model to be taken from the data base;

- a set of operational instructions enables a wide scale of model experiments to be defined in the system using various calculation techniques (linear programming, nonlinear programming, simulation techniques including the Monte-Carlo method, etc.); it also enables to choose the range and the required precision of experiments; the combination of "elementary" functions brought about by control instructions permits the solution of a wide set of "global" goals to be retained in the system;

- output instructions define the form (scope, depth and character) of the output information which is characteristic for the result of the model experiment.

3. Structure of the Multimodel of the electric power system

In Fig.3 is characterized in more detail the structure of the data base, of the results base and of the proper system of mathematical models.

In the data base is a detailed description of the numerical charateristics:

- predictions of the development of all subsystems of the environment of the modelled system,
- technical and economical characteristics of all elements of the subsystems of the generating basis and of the transmission networks of the modelled system (including the elements which could become a part of the modelled system during the calculation period),
- parameters of the stochastic process of the subsystem of electricity consumption in the modelled system.

The basic models of the model system are the following:

(i) a linearized model of the electric power system as a whole to be used for the optimization of its structure with respect to the assumed development of the environment and to the development of the technical and economical parameters of the prospective power system elements;

(ii) a model of the development of the power system generating basis which permits generating the time development of particular electric power system structures and introducing any corrections into the latter ("to build" new power plants or to shut them down in the model), defining the reliability of the electric power system when satisfying the demands of electricity consumers (by different analytical methods or simulation methods), fixing the demands on maintenance and generating sample schedules for the overhauls of generating units;

(iii) a model of the prospective regimes of the electric power system which permits investigating the most probable (technically) and economically optimum) prospective regimes of the subsystems and the elements of the systems which are "built up" in the model in any times section of the calculation period);

(iv) a model of the development of transmission networks which completes the chosen "model strategy" of the generating basis development with an adequate transmission network;

(v) a model of economic phenomena permitting investigation of the time development of individual types of costs of the development of the electric power system and of its subsystems in future and in present values, to evaluate the economical effectiveness of the variant under study,etc.

4. Information produced by the model system

In Figs.4,5,6,7 is graphically represented the most important information being produced by some models of the system.

Fig.4 illustrates the results obtained by the linear model. It demonstrates the position of individual types of power plants in the annual generation duration curve resulting from the process of the optimum choice of the electric power system structure for the given year of the optimization period. Fig.5 has been derived from the analysis of several interacting solutions and presents a view on the development of optimum proportions of individual types of power plants (including their unit power outputs) within the period of 20 years. The development is satisfactory from the point of view of the development of the environment, mainly of primary energy sources, and from the point of view of economy it is near the optimum state.

In Fig.6 are graphically represented the most inportant results of the analysis of the reliability index of the electric power system whose structure develops in the above mentioned way depending on the magnitude of power reserves in the system.

Prospective regimes of the investigated electric power system structure on the chosen day of the development period and for the chosen magnitude of power reserves are documentated in Fig.7. There can be seen a probable role of individual types of power plants in covering a particular daily load curve of the winter working day.

5. Experimentation with the Multimodel

A corresponding data base being at hand, the experiments with the Multimodel are reduced to listing the instructions of the ESM language and of their parameters. A procedure example is given in Fig.8.

6. Conclusion

The Multimodel is a highly effective model system providing wide possibilites of experimenting with the model system. The utilization of the data base (its content is being prepared by a specialised team) relieves the modeller of data preparation and extraordinarily increases the reliability of the calculation process.

The Multimodel represents an important step in the division of labour between the computer and man; the algorithms of the model take full care of elaborating the calculation shape of the model.

The utilization of the communication language and of the data base, as well as securing the internal communication in the model, ensure a continuous man-computer-man interaction.

The Multimodel is capable of being further developed, e.g. in applying it in the field of the historical data treatment, in preparing the prognosis of the development of environmental subsystems and of the subsystem of electricity consumption, in the modelling of the complex energy supply and of large-scale interconnections of the electric power systems of many countries, as well as in modelling the influence of power plants on the environment. Some work in this direction has already been started.

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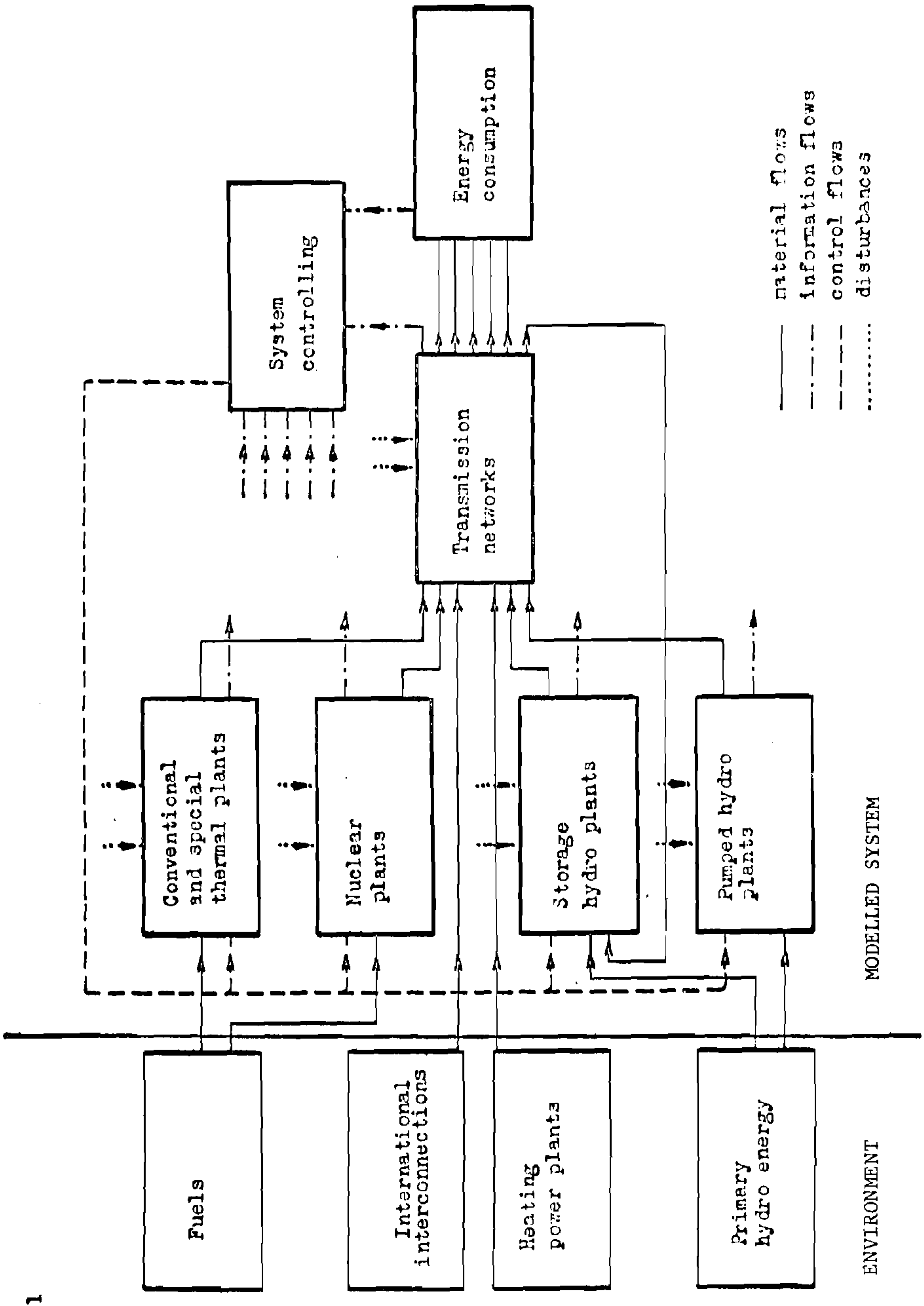

Energy consumption
System controlling
Transmission networks
Conventional and special thermal plants
Nuclear plants
Storage hydro plants
Pumped hydro plants
Fuels
International interconnections
Heating power plants
Primary hydro energy
MODELLED SYSTEM
ENVIRONMENT
material flows
information flows
control flows
disturbances

Fig.1

Fig. 2

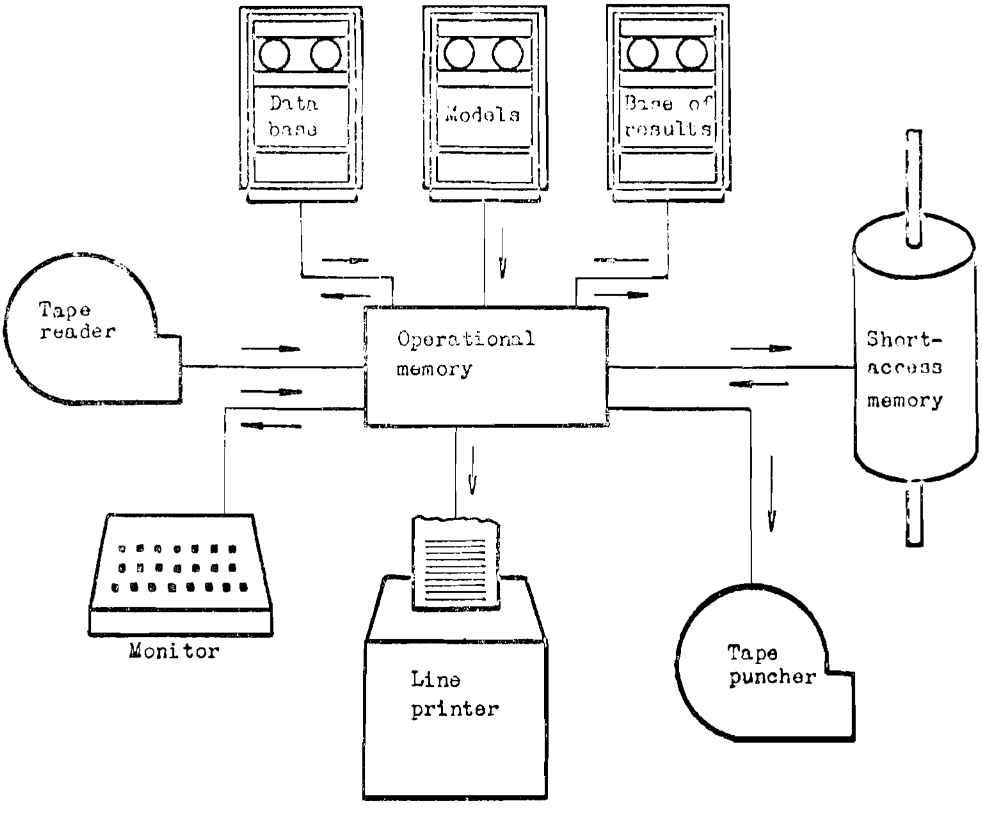
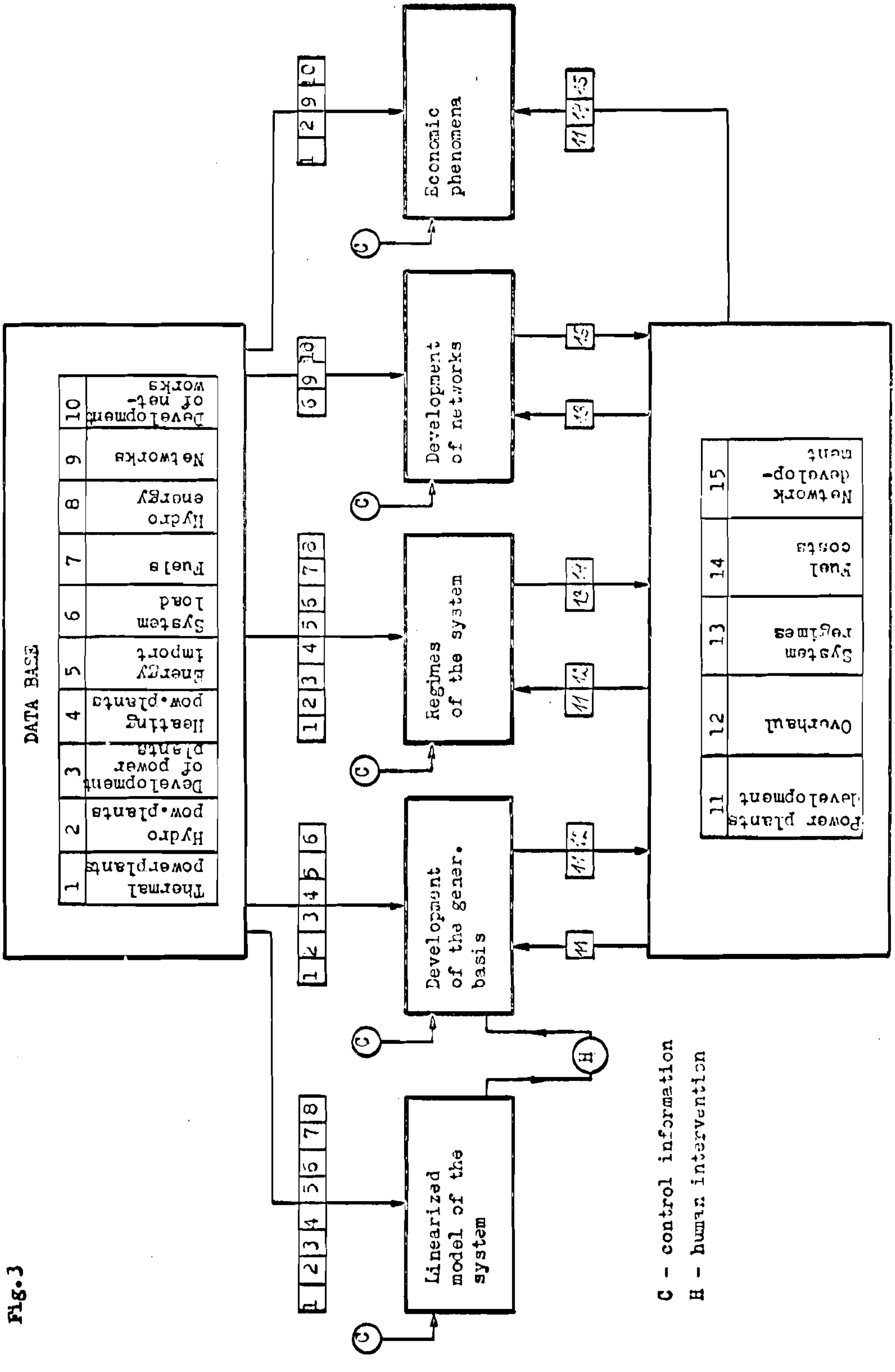

Data base
Models
Base of results
Tape reader
Operational memory
Short-access memory
Monitor
Line printer
Tape puncher

Fig.3



C - control information

H - human intervention

Fig.4

GT - gas turbine units
PHP - pumped storage plants
SHP - storage hydro plants
THP - conventional thermal power plants
NP - nuclear power plants

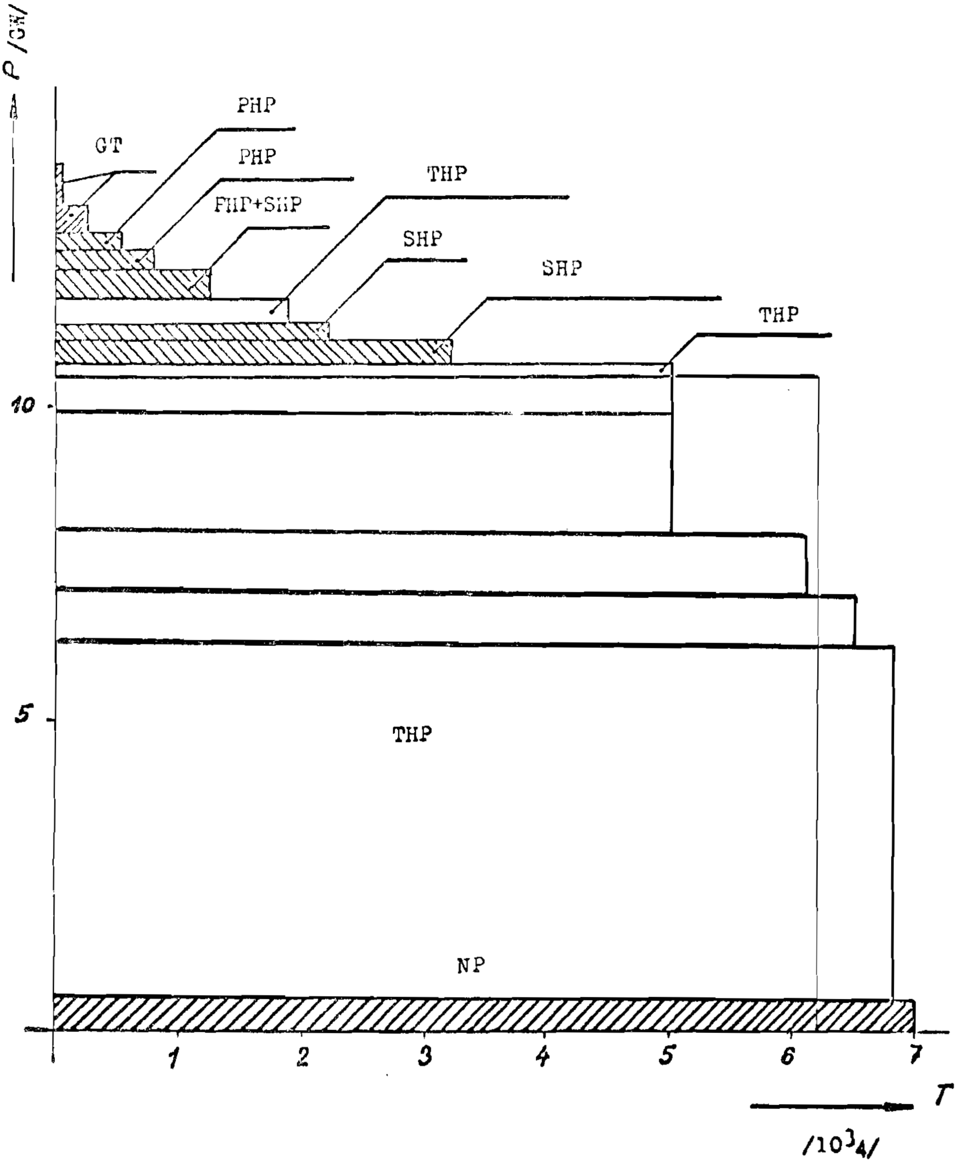
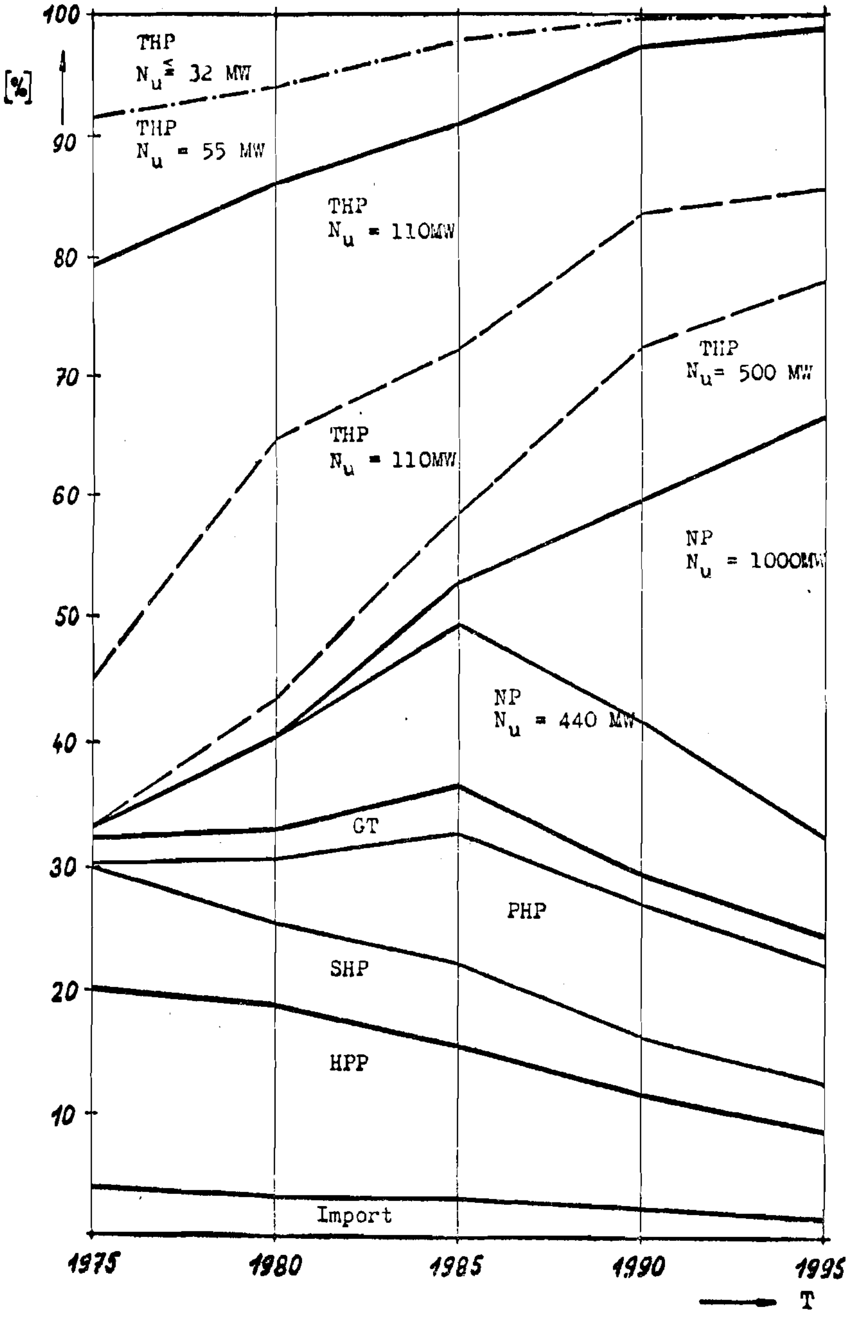


Fig. 5



THP - conventional thermal power plants
NP - nuclear plants
GT - gas turbine units
PHP - pumped hydro plants
SHP - storage hydro plants
HPP - heating power plants

Fig. 6

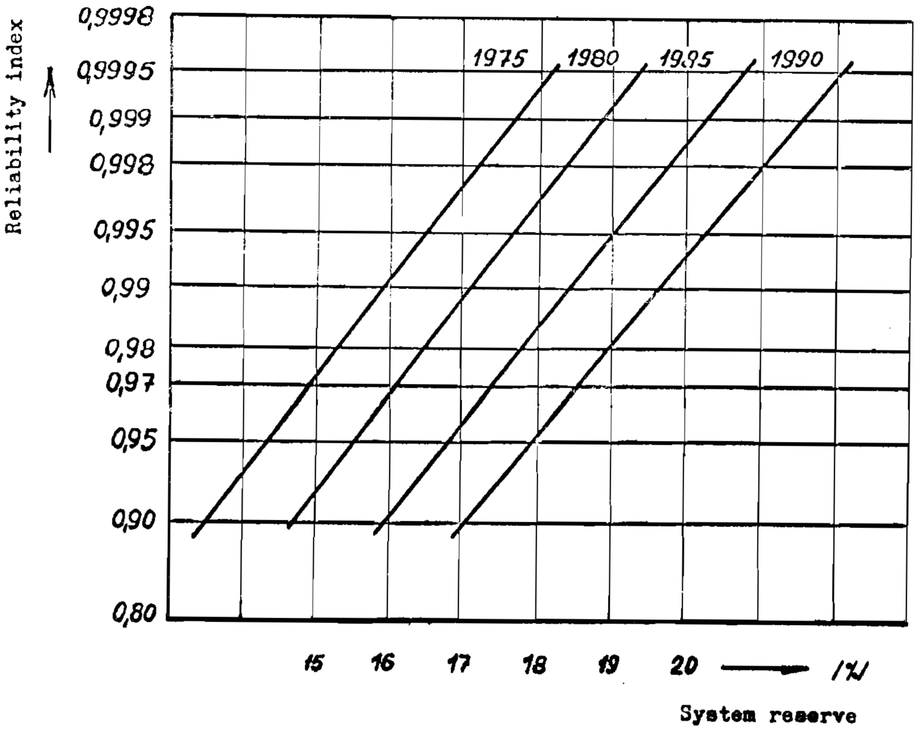

Reliability index
0,9998
0,9995
0,999
0,998
0,995
0,99
0,98
0,97
0,95
0,90
0,80
1975
1980
1985
1990
15
16
17
18
19
20
/%/
System reserve

Fig.7

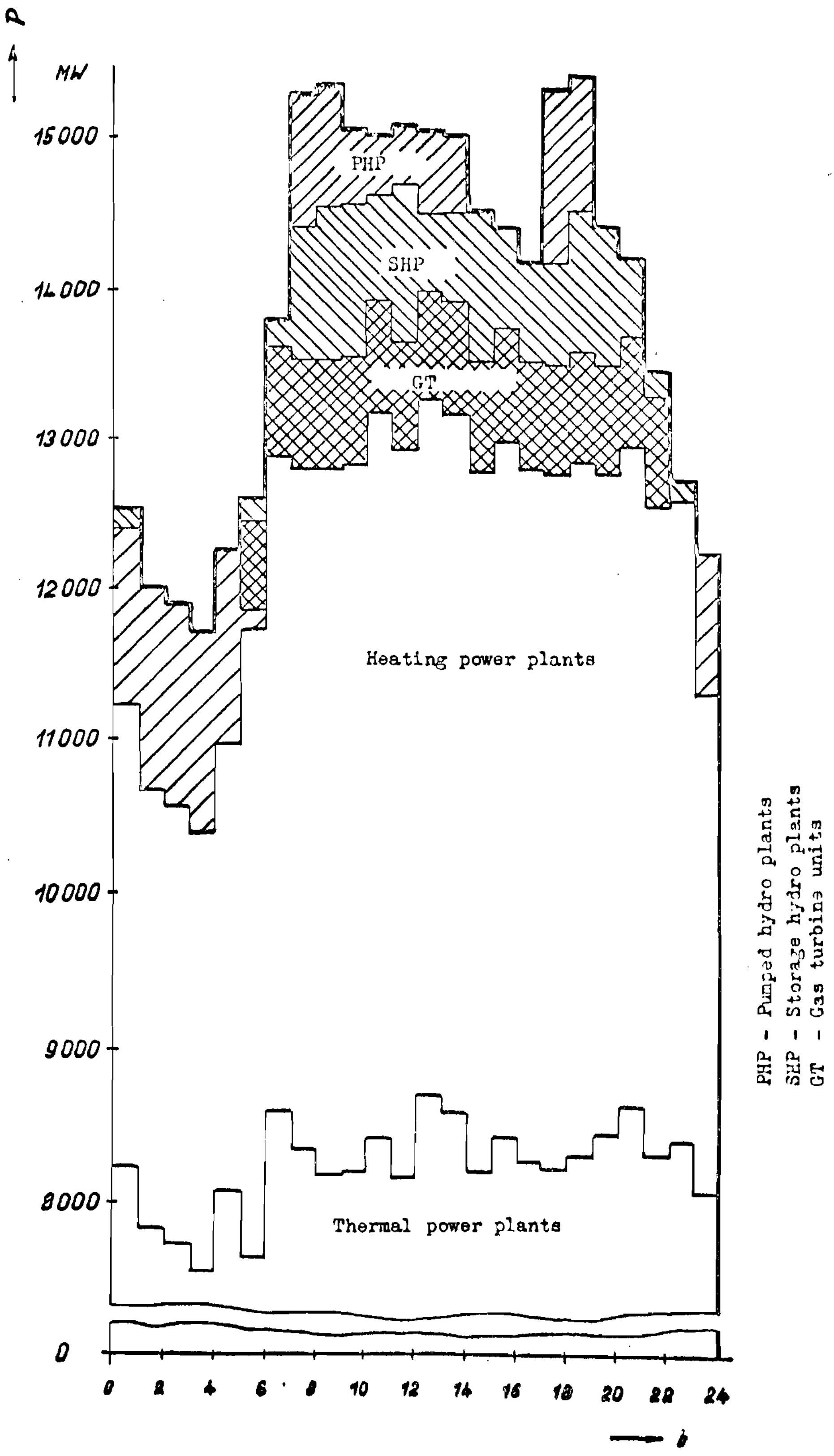

P
MW
15000
14000
13000
12000
11000
10000
9000
8000
0
PHP
SHP
GT
Heating power plants
Thermal power plants
0
2
4
6
8
10
12
14
16
18
20
22
24
h
PHP - Pumped hydro plants
SHP - Storage hydro plants
GT - Gas turbine units

Fig.8

Instruction	Function
PREPARE THE M 0000175 HYD M 0000175 LOA M 0000175 GEN M 0000275 VAR P ENDPR	Instruction "PREPARE" introduces a group of input commands. Data files symbolically marked THE, HYD and coded by a numerical code are taken from the data base. The letter P following the symbolical name of the file indicates the information to be taken from the punched tape.
DEVELOP 1975 1980 1.19 60 8 3 6 4	Operational instruction activates the algorithm which generates the development of the generating basis in the period 1975-1980 according to the given parameters.
BALANCE 1980	Output instruction making the line printer print a detailed power balance for 1980.
L IST	On the line printer appears a list of power plants indicating the terms of their building generated by the instruction "DEVELOP".
OVER 1980 1.1 1.3 2	A schedule of power plant overhauls will be generated for 1980.
SECSIB 1980 4 13 26 39 51	By means of the Monte-Carlo method the reliability index of the electric power system during the chosen weeks will be investigated.
OUTPUT OUTOVE P ENDOUT	Instruction "OUTPUT" introduces a group of output commands. On the tape puncher appear the data of the generating unit overhaul schedule.
WAIT	The computer waits for further instructions.

Discussion

Mr. Manne (IIASA) had a question about the present value criterion. He asked what discount rate they used numerically. Mr. Lencz replied that they used a discount rate of 10%. One delegate then asked if this model had been used in any decision making process. Mr. Lencz said that the model is used as a basis for the decision making in the Ministry of Energy and Fuel.

Another delegate asked whether the model could become fully available to IIASA. Mr. Lencz answered in the affirmative.

Another participant inquired whether they have compared their model with any other existing models. Mr. Lencz replied that they have some experience with linear programming models and also with simulations models. Finally, he stressed that the combination of these two modelling techniques as they use it now comes up to be saving computing time and also representing reality more precisely in the planning horizon.

Mr. Modemann (FRG) asked if the subprograms shown in figure 1--and there are many--are all interacting at the same time. Mr. Drahny replied that at the moment they are trying to improve the different submodels to get a compatible system. Up to now most of these models have been used separately.

Mr. Häfele asked what input data they used numerically for the nuclear fuel cycle, which means what reprocessing cost they used etc. Mr. Drahny said that they use the data which are available in the CSSR for the LWR; four of them are under construction now. The data concerning the future plants--each with 1000 MW/block--are in accordance with prognostic studies that have already been done.

U.S. ENERGY POLICY AND ECONOMIC GROWTH, 1975-2000

Edward A. Hudson and Dale W. Jorgenson

1. Introduction

The dramatic increase in world petroleum prices associated with the Arab oil embargo of October 1973 has highlighted the need for a new approach to the quantitative analysis of economic policy. Econometric models in the Tinbergen-Klein mold have proved to be very useful in studying the impact of economic policy on aggregate demand.[1] At the same time these models do not provide an adequate basis for assessing the impact of economic policy on supply. Input-output analysis in the form originated by Leontief is useful for a very detailed analysis of supply, predicated on a fixed technology at any point of time.[2] Input-output analysis does not provide a means of assessing the impact of changes in technology induced by price variations associated with changes in economic policy.

The purpose of this paper is to present a new approach to the quantitative analysis of U.S. energy policy.[3] This approach is based on an integration of econometric modeling and input-output analysis and incorporates an entirely new methodology for assessing the impact of economic policy on supply. We combine the determinants of energy demand and supply within the same framework and relate patterns of U.S. economic growth to both demand and supply. Our approach can be used to project U.S. economic growth and energy utilization for any proposed U. S.

energy policy. It can be employed to study the impact of specific policy changes on energy demand and supply, energy price and cost, energy imports and exports, and on U.S. economic growth.

The first component of our framework for energy policy analysis is a macro-econometric growth model. The complete model consists of endogenous business and household sectors and exogenous foreign and government sectors. The chief novelty of our growth model is the integration of demand and supply conditions for consumption, investment, and labor. The model is made dynamic by links between investment and changes in capital stock and between capital service prices and changes in investment goods prices. The model determines the components of gross national income and product in real terms and also determines their relative prices.

Our approach to the analysis of macro-economic activity can be contrasted with the analysis that underlies macro-econometric models used for short-term forecasting. Short-term forecasting is based on the projection of demand by foreign and government sectors and the determination of the responses of households and businesses in the form of demands for consumption and investment goods. The underlying economic theory is essentially the Keynesian multiplier, made dynamic by introducing lags in the responses of households and businesses to changes in income. In short-term macro-econometric models the supply side is frequently absent or present in only rudimentary form.[4] Our approach integrates the determinants of demand employed in conventional macro-econometric models with the determinants of supply.

The second component of our framework for energy policy analysis is an econometric model of inter-industry transactions for nine domestic industries. We have sub-divided the business sector of the U.S. economy into nine industrial groups in order to provide for the detailed analysis of the impact of U.S. energy policy on the sectors most directly affected by policy changes. The nine sectors included in the model are:

1. Agriculture, non-fuel mining, and construction.
2. Manufacturing, excluding petroleum products.
3. Transportation.
4. Communications, trade, and services.
5. Coal mining.
6. Crude petroleum and natural gas.
7. Petroleum refining and related industries.
8. Electric utilities.
9. Gas utilities.

Our inter-industry model includes a model of demand for inputs and supply of output for each of the nine industrial sectors. The model is closed by balance equations between demand and supply for the products of each of the nine sectors.

The principal innovation of our inter-industry model is that the input-output coefficients are treated as endogenous variables rather than exogenously given parameters. Our model for producer behavior determines the input-output coefficients for each of the nine sectors listed above as functions of the prices of products of all sectors, the prices of labor and capital services, and the prices of competing imports. We determine the prices of all nine products and the matrix of input-output coefficients simultaneously. In conventional input-output analysis the technology of each sector is taken as fixed at any point of time. Prices are determined as functions of the input-output coefficients, but the input-output coefficients themselves are treated as exogenously given parameters. Our approach integrates conventional input-output analysis with a determination of the structure of technology through models of supply for each industrial sector.

Given a framework that incorporates the determinants of demand and supply for energy in the U.S. economy, our first objective is to provide a reference point for the analysis of energy policy by establishing detailed projections of demand and supply, price and cost, and imports and exports for each of the nine industrial sectors included in our model. For this purpose we project the level of activity in each industrial sector and relative prices for the products of all sectors for the years 1975-2000. Our projections include the level of macroeconomic activity in the U.S. economy and the matrix of input-output coefficients for each year. Projections for the five industrial sectors that form the energy sector of the U.S. economy provide the basis for translating our detailed projections into the energy balance framework that has become conventional in the analysis of patterns of energy utilization.[5]

Our inter-industry approach imposes the same consistency requirements as the energy balance approach, namely, that demand is equal to supply in physical terms for each type of energy. In addition, our approach requires that demand and supply are consistent with the same structure of energy prices. This additional consistency requirement is absent from energy balance projections and requires the integration of energy balance projections with projections of energy prices. Our inter-industry model provides a means of combining these projections within a framework that also includes prices and inter-industry transactions for the sectors that consume but do not produce energy.

To illustrate the application of our model to the analysis of U.S. energy policy we have analyzed the effects of tax policies to stimulate energy conservation on the future pattern of energy utilization. Our methodology for policy analysis begins with a set of projections that assume no major new departures in energy policy. We then prepare an alternative set of projections incorporating the proposed change in policy. In analyzing the impact of tax policy we have incorporated the effect of energy taxes on demand and supply for energy. We find that price increases provide the economic incentive for the adoption of energy conservation measures that will result in considerable savings of energy. Tax policies or other measures to increase the price of energy could result in U.S. independence from energy imports by 1985.

We present our macro-econometric growth model in Section 2 of the paper. We then outline our model for inter-industry transactions in Section 3. In Section 4 we present econometric models of producer behavior for each of the nine sectors included in our inter-industry model. In Section 5 we present projections of economic activity and energy utilization for the period 1975-2000. In Section 6 we discuss a tax program for stimulating energy conservation and eliminating reliance of the U.S. economy on energy imports.

2. Growth Model

2.1. Introduction

The first component of our framework for energy policy analysis is a model of long-term U.S. economic growth. Our approach to the explanation of economic growth is closely related to the neo-classical theory of economic growth.[6] The building blocks of our model are sub-models of household and production sectors and sub-models of foreign and government sectors. The behavior of the household and production sectors is endogenous to the model, while the behavior of foreign and government sectors is exogenous.

Economic growth results from the link between current capital formation and future productive capacity. In our model this link is provided by a macro-econometric production function, relating the output of consumption and investment goods to the input of capital and labor services. Preferences between present and future consumption, which determine the allocation of income between saving and consumption, complete our model of economic growth.

Our macro-econometric growth model of the U.S. economy provides for the simultaneous determination of the values of products and factors of production in both current and constant prices. The model links demand for capital formation by savers to the supply of investment goods by producers. Similarly, the model links demand for consumption goods and supply of labor services by households to supply of consumption goods and demand for labor by producers. Finally, given the supply of capital stock, the demand for capital services determines the overall rate of return to capital.

The theory of U.S. economic growth that underlies our macro-econometric growth model is a theory of the behavior of the private sector of the U.S. economy. The behavior of the foreign and government sectors is taken to be exogenous. Demographic trends -- the growth of population, labor force, and unemployment -- are also exogenous to the model. The main determinant of growth in productivity is capital formation. Growth in productivity over and above growth due to capital formation is exogenous to the model. We have projected demographic trends and trends in productivity growth on the basis of past-war experience in the United States.[7]

2.2. Variables

Our econometric growth model is summarized in the following series of tables. In Table 1 we present our notation for the variables that appear in the model. The first group of variables convert aggregares from one basis of classification to another. For example, the index of total factor productivity A converts input to output. The index of AW converts investment weights for capital formation to the weights appropriate for the measurement of wealth. All of the aggregation variables are taken to be exogenous.

The second group of variables appearing in Table 1 comprises the quantities of products and factors of production, broken down by sector of origin and destination. Variables beginning with C are quantities of consumption goods. Similarly, variables beginning with I are quantities of investment goods. Variables beginning with L are quantities of labor services, while variables beginning with K are quantities of capital services. The third group of variables includes prices

Table 1. Macro-econometric growth model: notation.

1. Aggregation variables.

A	Total factor productivity (input to output).
ACI	Investment to change in business inventories, consumption goods.
AI	Investment to capital stock.
AL	Investment to capital stock, lagged.
AK	Capital stock, lagged to capital service.
APC	Implicit deflator of consumption goods to implicit deflator of change in business inventories, consumption goods.
AW	Investment to wealth.

2. Quantities.

C	Personal consumption expenditures, including services of consumers' durables.
CE	Supply of consumption goods by government enterprises.
CG	Government purchases of consumption goods.
CI	Change in business inventories of consumption goods.
CR	Net exports of consumption goods, less income originating, rest of the world.
CS	Supply of consumption goods by private enterprises.
G	Net claims on government.
R	Net claims on rest of the world.
I	Gross private domestic investment, including purchases of consumers' durables.
IG	Government purchases of investment goods.
IR	Net exports of investment goods.

Continued

Table 1 (continued)

IS	Supply of investment goods by private enterprises.
L	Supply of labor services.
LD	Private purchases of labor services.
LGE	Government enterprises purchases of labor services.
LGG	General government purchases of labor services.
LH	Time available.
LJ	Leisure time.
LR	Net exports of labor services.
LU	Unemployment.
K	Capital stock.
KD	Capital services.

3. Prices.

PC	Implicit deflator, personal consumption expenditures, including services of consumers' durables.
PCE	Implicit deflator, supply of consumption goods by government enterprises.
PCG	Implicit deflator, government purchases of consumption goods.
PCI	Implicit deflator, change in business inventories of consumption goods.
PCR	Implicit deflator, net exports of consumption goods, less income originating, rest of the world.
PCS	Implicit deflator, supply of consumption goods by private enterprises.
PG	Implicit deflator, net claims on government.
PR	Implicit deflator, net claims on rest of the world.
PI	Implicit deflator, gross private domestic investment, including purchases of consumers' durables.

Continued

Table 1 (concluded)

PIG	Implicit deflator, government purchases of investment goods.
PIR	Implicit deflator, net exports of investment goods
PIS	Implicit deflator, supply of investment goods by private enterprises.
PL	Implicit deflator, supply of labor services.
PLD	Implicit deflator, private purchases of labor services.
PLGE	Implicit deflator, government enterprises purchases of labor services.
PLGG	Implicit deflator, general government purchases of labor services.
PLR	Implicit deflator, net exports of labor services.
PKD	Implicit deflator, capital services.

4. Financial variables.

D	Rate of depreciation, private domestic tangible assets.
M	Rate of replacement, private domestic tangible assets.
N	Nominal rate of return, private domestic tangible assets.
S	Gross private national saving.
W	Private national wealth.

5. Tax and transfer variables.

EL	Government transfer payments to persons, other than social insurance funds
TC	Effective tax rate, consumption goods.
TI	Effective tax rate, investment goods.
TK	Effective tax rate, capital services.
TL	Effective tax rate, labor services.
TP	Effective tax rate, capital stock.

corresponding to the quantities of products and factors of production. Each price begins with P and continues with the corresponding quantity. For example, the variable C is personal consumption expenditures and the variable PC is the price of personal consumption expenditures.

The fourth group of variables are financial variables: rates of depreciation and replacement, the nominal rate of return, gross private national saving, and private national wealth. Finally, the fifth group of variables are tax and transfer variables. The variable EL represents government transfer payments to persons other than social insurance funds, an expenditure category. The variables beginning with T are tax rates. Each of the products and factors included in the model -- consumption goods, investment goods, capital services, and labor services -- is associated with an effective tax rate. The variable TP is the effective tax rate for capital stock.

2.3. Equations.

Next we present the equations for our macro-econometric growth model. The model includes five behavioral equations, describing the behavior of household and business sectors.[8] The level of household expenditure on consumer goods and services is determined by the wealth and resources held by the household sector, including the time resources held:

$$PC*C = 0.0034*W(-1) + 0.1469*PL*LH + 0.1469*EL$$

where

PC = price of consumer goods and services facing buyers of these goods (implicit deflator for consumers goods)

C = quantity of consumer goods and services purchased by the household sector

W(-1) = value of the wealth (the value of both financial and real assets) held by the household sector at the beginning of the year

PL = price of labor services received by the worker (implicit deflator for labor services)

LH = total time available to the household sector

EL = government transfer payments, other than social insurance benefits, to persons

The desired amount of work input provided by the household sector is determined by the total amount of time available, the wage rate, and the extent of other resources available to the household sector in the form of wealth and transfer payments.

$$PL*L = -0.0196*W(-1) - 0.8403*EL + 0.1597*PL*LH$$

where

PL = implicit deflator for labor services

L = supply of labor services by the household sector

W(-1) = total private wealth at the beginning of the year

EL = government transfers, other than social insurance benefits, to persons

LH = total time available to the household sector.

The demand for labor is determined by the total level of production, the amount of capital services available, and the relative prices of capital and labor services.

$$PLD*LD = 1.5655*PKD*KD$$

where

PLD = price of labor services to the purchasing company (implicit deflator, private purchases of labor services)

LD = purchases of labor services for production in the private sector

PPKD = implicit price deflator for capital services

KD = available supply of capital services.

Output of investment goods is determined by the price of investment goods, the prices of capital services and the available supply of capital services, and the amount of productive capacity being devoted to the output of consumer goods and services.

$$PIS*IS = PKD*KD*(1.1717 - 0.5006*\log(CS) + 0.5006*\log(IS))$$

where

PIS = implicit price deflator for the supply of investment goods by private enterprices

IS = supply of investment goods by the private sector

PKD = implicit price deflator for capital services

KD = available supply of capital services

CS = output of consumption goods and services by the private sector.

The output of production that takes place in the U.S. private sector, whether of consumption or of investment goods, is limited by the total productive capacity which in turn depends on available supplies of capital and labor services as well as on the level of technology.

$$1.3938*\log(CS) + 1.1717*\log(IS) + 0.2503*(\log(CS) - \log(IS))^2$$

$$= \log(KD) + 1.5655*\log(LD) + 2.5655*\log(A)$$

where

CS = output of consumption goods and services by the private sector

IS = output of investment goods by the private sector

KD = available supply of capital services

LD = amount of labor services purchased by the private sector

A = index of the level of technological and organizational knowledge.

The behavioral equations of our macro-econometric growth model have been estimated from historical data for the United States for the period 1929-1969.[9] In addition to the five behavioral equations in the model includes accounting identities for capital stock, investment and capital services, for the value of input and output, for saving and wealth, and for the value of consumption goods, investment goods, capital services, and labor srevice. These accounting identities incorporate the budget constraints for household and business sectors and the flow of each product and factor of production in current prices.

The model is completed by balance between demand and supply of products and factors of production in constant prices and by aggregation equations that determine inventory accumulation of consumption goods. Although gross private domestic investment is determined in the model, the allocation of investment between fixed investment and inventory accumulation is not determined in the model. An allocation between inventory accumulation in the form of consumption goods and other components of gross private domestic investment is required for the balance between demand and supply of consumption and investment goods. In Table 2 we present the equations for our macro-econometric growth model in tabular form.

Table 2. Macro-econometric growth model: equations.

1. Behavioral equations.

Investment supply:

$$\frac{PIS * IS}{PKD * KD} = 1.1717 - 0.5006 * (\log CS - \log IS).$$

Labor demand:

$$\frac{PLD * LD}{PKD * KD} = 1.5655.$$

Production possibility frontier:

$$0 = -\log KD - 1.5655 * \log LD + 1.3938 * \log CS - 2.5655 * \log A$$
$$+ 1.1717 * \log IS + 0.2503 * (\log CS - \log IS) ** 2.$$

Consumption demand:

$$PC * C = 0.0034 * W(-1) + 0.1469 * (PL * LH + EL).$$

Leisure demand:

$$PL * LJ = 0.0196 * W(-1) + 0.8403 * (PL * LH + EL).$$

2. Accounting identities:

Capital stock and investment:

$$K = AI * I + (1-M) * K(-1).$$

Capital service and capital stock:

$$KD = AK * K(-1).$$

Value of output and input:

$$PIS * IS + PCS * CS = PKD * KD + PLD * LD.$$

Continued

Table 2. (continued)

Value of consumption goods:

$$(1 + TC) * PCS * CS + PCE * CE$$

$$= PC * C + PCG * CG + PCI * CI + PCR * CR.$$

Value of investment goods:

$$(1 + TI) * PIS * IS + PCI * CI = PI * I + PIG * IG + PIR * IR.$$

Value of capital services:

$$(1 - TK) * (PKD * KD - TP * PI(-1) * AW(-1) * K(-1))$$

$$= N * PI(-1) * AW(-1) * K(-1) + D * PI * AL * K(-1)$$

$$+ PI(-1) * AW(-1) * K(-1) - PI * AL * K(-1).$$

Value of labor services:

$$(1 - TL) * (PLD * LD + PLGE * LGE + PLGG * LGG + PLR * LR) = PL * L.$$

Saving:

$$S = PI * I + PG * (G - G(-1)) + PR * (R - R(-1)).$$

Wealth:

$$W = PI * AW * K + PG * G + PR * R.$$

3. Balance equations.

Consumption:

$$CS + CE = C + CG + CI + CR.$$

Continued

Table 2. (concluded)

Investment:

$$IS + CI = I + IG + IR.$$

Time:

$$LH = L + LJ.$$

Labor:

$$L = LD + LGE + LGG + LR + LU.$$

4. Aggregation equations.

Implicit deflator, change in business inventories, consumption goods:

$$PCI = PC * APC.$$

Change in business inventories, consumption goods:

$$PCI * CI = PI * I * ACI.$$

In Table 3 we present a list of the variables that are endogenous to the model -- prices and quantities of consumption, investment, labor and capital, and the nominal rate of return, saving, and wealth. Table 3 also includes a list of variables exogenous to the model -- aggregation variables, demand by government and foreign sectors and their prices for consumption and investment goods anf for labor and capital services, and government tax rates and transfer payments. Finally, Table 3 includes lagged endogenous variables -- capital stock, the price of investment goods, and wealth.

Table 3. Macro-econometric growth model: classification of variables

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Endogenous variables:

C, CI, CS, I, IS, L, LD, LJ, K, KD, PC, PCI, PCS, PI, PIS, PL, PLD, N, S, W

Exogenous variables:

A, ACI, AI, AL, AK, APC, AW, CE, CG, CR, G, R, IG, IR, LGE, LGG, LH, LR, LU, PCE, PCG, PCR, PG, PR, PIG, PIR, PLGE, PLGG, PLR, PKD, D, M, TC, TI, TK, TL, TP, EL

Lagged endogenous variables:

K(-1), PI(-1), W(-1)

3. Inter-Industry Model

3.1. Introduction. The second component of our framework for energy policy analysis is a model of inter-industry transactions for nine domestic industries of the United States. The nine sector of the model were chosen to provide for detailed analysis of the impact of U.S. energy policy on the sectors most directly affected by policy changes. The nine sectors included in the model are:

1. Agriculture, non-fuel mining, and construction.
2. Manufacturing, excluding petroleum products.
3. Transportation.
4. Communications, trade, and services.
5. Coal mining.
6. Crude petroleum and natural gas.
7. Petroleum refining and related industries.
8. Electric utilities.
9. Gas utilities.

Our inter-industry model consists of balance equations between supply and demand for the products of each of the nine sectors included in the model. The model also includes accounting identities between the value of domestic availability of these products and the sum of values of intermediate input into each industry, value added in the industry, and imports of competing products. Demands for the products include demands for use as inputs by each of the nine sectors included in the model. The rest of domestic availability is allocated among four categories of final demand: personal consumption expenditures, gross private domestic investment, government expenditures, and exports.

In the model for projecting energy demand and supply we take the levels of final demand for all industries from the macro-econometric model. Second, for the five energy sectors of the model we take the price and quantity of imports to be exogenous. For the four non-energy sectors we take the prices of imports as exogenous and determine import quantities along with the quantities of capital and labor services in each industry.[10] The prices of capital and labor services are determined within the macro-econometric model. We take the quantities of exports and government purchases of the output of each industry as exogenous. We also take the allocation of investment among the industries of origin to be exogenous.

Our inter-industry model consists of models of producer behavior for each of the nine industries included in the model. Producer behavior in each industry can be characterized by input-output coefficients for the input of products of each of the nine sectors, inputs of capital and labor services, and, for the four non-energy sectors, the level of competitive imports. The essential novelty of our model of producer behavior is that the input-output coefficients are endogenous. The input-output coefficients are determined together with the prices of the outputs of each sector in the application of our inter-industry model to the projection of energy demand and supply.

An inter-industry approach to the study of energy resources is essential since most energy is consumed as an intermediate rather than a final product of the economy. Examples of intermediate products would be fossil fuels consumed by the electric generating sector. Examples of final products would be gasoline and heating oil consumed by the household and government sectors. Energy balance models used in most previous work project levels of both intermediate and final demand. The novelty of our approach is that energy balances are projected within a framework that also includes energy and non-energy prices. Most projections of energy balances ignore the effects of price changes on patterns of energy utilization.

Given the prices of domestic availability of the output of each sector included in our model, we determine the allocation of personal consumption expenditures among commodity groups distinguished in the model, using our model of consumer behavior. Personal consumption expenditures include deliveries to the household sector by eight of the nine sectors included in our inter-industry model of the producing sector. There are no direct deliveries of crude petroleum and natural gas to personal consumption expenditures. These products are delivered first to the petroleum refining and gas utility sectors and then to personal consumption expenditures and to other categories of intermediate and final demand.

Personal consumption expenditures also include non-competitive imports and the services of dwellings and consumers' durables. The levels of personal consumption expenditures on each of the eleven commodity groups included in our model of the household sector are determined from the projected level of personal consumption expenditures from the macroeconometric model, from the prices of domestic availability of the output of each sector included in the inter-industry model, and from the prices of non-competitive imports, consumers' durables services, and housing services. The price of non-competitive imports is taken to be exogenous.

The capital service prices for consumers' durables services and housing services are determined from the price of capital services determined in the macro-econometric model.

The equations representing the balance of demand and supply for each of the nine sectors of the inter-industry model set domestic availability equal to the sum of intermediate demands and final demand. Intermediate demands are determined simultaneously with the levels of output of each industry, given input-output coefficients determined in the model of producer behavior. The input-output coefficients are determined simultaneously with the prices of domestic availability of the output of each industry. Finally, levels of capital and labor services for all sectors and competitive imports for the four non-energy sectors are determined from the levels of domestic avillability and the corresponding input-output coefficients. These levels can be compared with the levels projected in the macro-econometric model.

3.2. Inter-industry Transactions. We first describe our model of inter-industry transactions and then outline the application of this model to the projection of energy demand and supply; our notation is as follows:

XIJ = intermediate demand for the output of industry I by industry J;

YI = final demand for the output of industry I;

XI = domestic availability of the output of industry I;

PI = price of the output of industry I.

To simplify the notation we take the price of the output of each industry to be the same in all uses. The deflators for each category of intermediate and final demand can differ. In projecting energy demand and supply we take the ratios of the deflator for the individual categories of demand to the deflator for domestic availability of output of the industry to be exogenous.

The inter-industry model consists of equality between demand and supply for each of the nine sectors included in the model. The balance equations for the nine sectors are:

$$XI = \sum_{J=1}^{9} XIJ + YI \qquad (I=1,2...9) \quad .$$

In addition, the model includes accounting identities between the value of domestic availability and the sum of values of intermediate input into the industry, value added in the industry, and, for the four-non-energy sectors, the imports of competing products:

$$PI*XI = \sum_{J=1}^{9} PJ*XJI + PK*KI + PL*LI + PRI*RI \qquad (I=1,2...9) \quad ,$$

where:

KI = quantity of capital services in industry I;

LI = quantity of labor services in industry I;

RI = competitive imports of the out put of industry I;

PK = price of capital services;

PL = price of labor services;

PRI = price of competitive imports of the output of industry I.

Again, prices of capital and labor services can differ among industries. To simplify notation we take the prices of these productive factors to be the same in all industries. In projecting energy demand and supply we take the ratios of service prices for each industry to the corresponding prices from the macro-econometric model to be exogenous.

Our inter-industry model includes models of producer behavior for each of the nine industrial sectors included in the model. These models of producer behavior can be derived from price possibility frontiers for the nine sectors:

$$AI*PI = GI(P1,P2,\ldots P9;\ PK,PL,PRI) \quad , \qquad (I=1,2\ldots 9) \quad ,$$

where AI (I=1,2...9) is an index of Hicks-neutral technical change in industry I. The price possibility frontier for each sector can be derived from price possibility frontiers for each of the three sub-models employed in our analysis of production structure:[12]

1. a model giving the price of output as a function of prices of four aggregate inputs in each sector -- capital (K), labor (L), energy (E), and materials (M);

2. a model giving the price of aggregate energy input in each sector as a function of the prices of the five types of energy included in the model -- coal, crude petroleum and natural gas, refined petroleum products, electricity,and gas as a product of gas utilities;

3. a model giving the price of aggregate non-energy input in each sector as a function of the prices of the five types of non-energy input into each sector -- agriculture, manufacturing, transportation, communications, and, for the four non-energy sectors, competitive imports.

Given the prices of capital services, labor services, and competitive imports in each of the four non-energy sectors, we can determine the prices of domestic availability of output PI (I=1,2...9) for all nine sectors. To determine these prices we solve twrnty-seven equations for prices of domestic availability, prices of aggregate energy input, and prices of aggregate non-energy input into all nine sectors. This system of twenty-seven equations consists of three equations for each sector. These three equations correspond to production possibility frontiers for each of the three sub-models for each sector. In these computations we are making use of a nonsubstitution theorem of the type first discussed by Samuelson.[12] This theorem states that for given prices of the factors of production and competitive imports, the prices of domestic availability of the output of each sector are independent of the composition of final demand.

The second step in our analysis of inter-industry transactions is to derive input-output coefficients for each of the nine industrial sectors included in our inter-industry model. The input-output coefficients can be expressed as functions of the prices. First, the relative share of the jth intermediate input can be determined from the identity:

$$\frac{\partial \ln PI}{\partial \ln PJ} = \frac{PJ*XJI}{PI*XI} = \frac{PJ}{PI} * AJI \qquad (I,J=1,2...9) \quad ,$$

where AJI is the input-output coefficient corresponding to XJI; it represents the input of the output of industry J per unit of output of industry I. Similar identities determine the relative shares of capital and labor services and competitive imports.[13]

Second, we can divide the relative shares by the ratio of the price of domestic availability of the output of the Jth industry PJ to the price for the Ith industry PI to obtain the input-output coefficients:

$$\frac{XJI}{XI} = AJI(P1,P2 \ldots P9;\ PK,\ PL,\ PRI) \quad , \qquad (I,J=1,2\ldots9);$$

and:

$$\frac{KI}{XI} = AKI(P1,P2 \ldots P9;\ PK,\ PL,\ PRI) \quad ,$$

$$\frac{LI}{XI} = ALI(P1,P2 \ldots P9;\ PK,\ PL,\ PRI) \quad ,$$

$$\frac{RI}{XI} = AMI(P1,P2 \ldots P9;\ PK,\ PL,\ PRI) \quad , \qquad (I=1,2\ldots9) \quad .$$

For each industry we derive the input-output coefficients in two steps: First, we determine the input-output coefficients for the aggregate inputs -- capital (K), labor (L), energy (E), and materials (M). Second, we determine the input-output coefficients for the input of each type of energy input per unit of total energy input and the input of each type of non-energy input per unit of total non-energy input. To obtain the input-output coefficients required for our inter-industry model we multiply the input-output coefficients for each type of energy by the input-output coefficient for total energy. Similarly, we multiple the input-output coefficients for each type of non-energy input by the input-output coefficient for total non-energy input. We obtain input-output coefficients for capital services, labor services, five types of energy inputs into each sector and give types of non-energy inputs into each sector.

The input-output coefficients for each of the nine industrial sectors included in our model of inter-industry transactions are functions of the prices of capital services, labor services, and competitive imports for the four non-energy sectors and the prices of domestic availability of the output of each of the nine sectors. The prices of domestic availability are functions of the prices of capital services, labor services, and competitive imports for the four non-energy sectors. By the nonsubstitution theorem both prices of domestic availability and input-output coefficients are independent of the composition of final demand.[14]

3.3. Final demand. Final demand for domestic availability of the output of each of the nine sectors included in our inter-industry model is allocated among personal consumption expenditures, gross private domestic investment, government expenditures, and exports. In projecting energy demand and supply we take aggregate levels of each category of final demand from our macro-economic projections. We allocate personal consumption expenditures among the nine sectors included in our model, employing aggregate personal consumption expenditures as total expenditures, on the basis of the prices of domestic availability of the output of all nine sectors. Government expenditures and exports of the output of each sector are exogenous. Imports of the output of the five energy sectors are also exogenous so that we include only exports net of imports in final demand for these sectors. We take aggregate private domestic investment from our macro-economic projections. We take the relative proportion of investment in the output of each industrial sector included in our inter-industry model to be exogenous.

The final step in determining the level and composition of inter-industry transactions is to determine the levels of output, employment, and utilization of capital for each of the nine industrial sectors included in our model and competitive imports for the four non-energy sectors included in the model. This part of our model coincides with conventional input-output analysis. Given the input-output coefficients for all nine sectors, we can determine the level of output for each sector for any given levels of final demand for the output of all nine sectors. We present projected matrices of inter-industry transactions in energy for the years 1975, 1985 and 2000 in Section 5 below. We also present projections of energy prices for each year.

Final demand for domestic availability of the output of each of the nine sectors included in the model is allocated among consumption, investment, government expenditures, and exports:

$$YI = CI + II + GI + ZI \quad , \quad (I=1,2...9) \quad ,$$

where:

CI = personal consumption expenditures on the output of industry I;

II = gross private domestic investment in the output of industry I (the sum of gross private fixed investment and net inventory change);

GI = government expenditure on the output of industry I;

ZI = exports of the output of industry I (exports less imports for the five energy sectors).

In our model for projecting energy demand and supply we take the levels of final demand for all industries from the macro-economic projections. We link our inter-industry model to our macro-econometric model through the identities:

$$PC*C = \sum_{I=1}^{9} PI*CI \quad ,$$

$$PI*I = \sum_{I=1}^{9} PI*II \quad ,$$

$$PG*G = \sum_{I=1}^{9} PI*GI \quad ,$$

$$PZ*Z = \sum_{I=1}^{9} PI*ZI \quad .$$

The values of personal consumption expenditures PC*C, gross private domestic investment PI*I, government expenditure PG*G, and exports PZ*Z from the macro-econometric model are set equal to the sums of each of these categories of expenditures over all nine industries included in the inter-industry model.

In the macro-econometric model government expenditures on goods and services are divided into two parts:

$$PG*G = PIG*IG + PCG*CG \quad ,$$

where

IG = quantity of government expenditures on investment goods;

CG = quantity of government expenditures on consumption goods;

PIG = price of government expenditures on investment goods;

PCG = price of government expenditures on consumption goods.

In making projections of energy demand and supply we project total government expenditures in current and constant prices. Government expenditures on goods and services are exogenous to the macro-econometric model. We then allocate total government expenditures among the nine industry groups included in the inter-industry model.

In our macro-econometric model net exports of goods and services are taken to be exogenous. For the purposes of projecting energy demand and supply we divide net exports between imports and exports, allocate exports among the nine industry groups included in the model, and project the prices of competitive imports for each of the nine sectors of the model. Since net exports in current and constant prices are exogenous to the macro-econometric model, this change in the treatment of net exports does not alter the structure of the complete model. In projecting energy demand and supply we take the prices of imports for each industrial sector together with levels of capital and labor services for each sector.

We project gross private domestic investment in current and constant prices in our macro-econometric model. To project energy demand and supply we allocate gross private domestic investment among the nine industry groups included in the model. The relative proportions of investment originating in each sector is taken to be exogenous. In a completely dynamic model the allocation of investment by sector of origin and sector of destination would be endogenous. Our macro-econometric model incorporates the dynamics of saving and investment only in the projection of total investment. The allocation of capital by sector of destination is endogenously determined, but the allocation of investment by sector of origin in exogenous.

The final step in determining final demand for the domestic availability of the output of each sector included in our inter-industry model is to allocate personal consumption expenditures among the products of the nine sectors included in the model and expenditures on non-competitive imports and the services of consumers' durables, which are not included among the products of the nine sectors. For this purpose we employ an econometric model of consumer behavior. This model is based on an indirect utility function that can be represented in the form:[15]

$$\ln V = \ln V \left(\frac{P1}{PC*C}, \frac{P2}{PC*C} \cdots \frac{P11}{PC*C} \right)$$

where V is the level of utility, PI is the price of the Ith commodity, and PC*C is total personal consumption expenditures. There are eleven commodity groups included in our model of consumer behavior: one for each of the nine industrial sectors, excluding crude petroleum and natural gas, housing, services of consumers' durables and non-competitive imports.

For each commodity group we take the budget share to be fixed. This assumption corresponds to a linear logarithmic indirect utility function. The quantity demanded for each of the eleven commodity groups included in our model of consumer behavior is a function of the prices of the corresponding commodity group and the level of total personal consumption expenditures. We determine the level of total personal consumption expenditures in our macro-econometric model. We determine the prices of domestic availability of the output of each sector in the inter-industry model from our models of producer behavior. Given total expenditures and the prices, we can determine the quantities demanded of the output of each sector of the model for personal consumption expenditures.

Final demand for all nine industrial sectors included in our inter-industry model is the sum of final demands for personal consumption expenditures, gross private domestic investment, government expenditures, and exports. We add personal consumption expenditures for the output of communications, trade and services, less housing, to personal consumption expenditures for housing to obtain personal consumption expenditures on communications, trade and services. Otherwise, there is a direct correspondence between commodity groups in our model of consumer behavior and the sectors included in our inter-industry model. Given all final demands, the prices of domestic availability of the output of each sector and the matrix of input-output coefficients, we can determine the matrix of inter-industry transactions in both current and constant prices.

The equations representing the balance of demand and supply for each of the nine industrial sectors included in our inter-industry model can be preresented in the form:

$$XJ = \sum_{J=1}^{9} XIJ + YI$$

$$= \sum_{J=1}^{9} AIJ*XJ + CI + II + GI + ZI \quad , \qquad (I=1,2...9) \quad .$$

The input-output coefficients {AIJ} are determined together with the prices of domestic availability of the output of each industry {PI}. Given prices and the level of aggregate personal consumption expenditures, the levels of personal consumption expenditures {CI} are determined. The remaining components of final demand {II,GI,ZI} are projected by industry of origin. These projections are consistent with levels of gross private domestic investment, government expenditures and exports from our macro-econometric model.

In matrix form the demand and supply balance equation for the model can be represented as:

$$x = Ax + y \quad ,$$

where x and y are vectors of outputs and final demands:

$$x = \begin{matrix} X1 \\ X2 \\ \vdots \\ X9 \end{matrix} \quad , \qquad y = \begin{matrix} Y1 \\ Y2 \\ \vdots \\ Y9 \end{matrix} \quad ,$$

and A is the matrix of input-output coefficients:

$$A = \begin{matrix} A11 & A12 & \cdots & A19 \\ A21 & A22 & \cdots & A29 \\ \vdots & \vdots & & \vdots \\ A91 & A92 & & A99 \end{matrix} \quad .$$

Levels of domestic availability of the output of each sector are obtained by solving this system of equations:

$$x = (I-A)^{-1}y \quad .$$

We refer to the matrix $(I-A)^{-1}$ as the matrix of final demand multipliers.

Levels of capital and labor services and competitive imports are determined from the levels of domestic availability and the corresponding input-output coefficients:

$$KI = AKI*XI \quad ,$$

$$LI = ALI*XI \quad ,$$

$$MI = AMI*XI \quad , \qquad (I=1,2...9) \quad .$$

The input-output coefficients aor capital and labor services and competitive imports are functions of the prices of the outputs of the nine sectors included in our inter-industry model, the prices of capital and labor services and the prices of competitive imports for the four non-energy sectors of the model.

4. Producer Behavior.

4.1. Introduction. Our inter-industry model includes models of producer behavior for each of the nine industrial sectors included in the model.[16] These models of producer behavior can be derived from the price possibility frontiers for the corresponding sectors. The input-output coefficients for intermediate inputs and for inputs of capital services, labor services, and competitive imports for the non-energy sectors are functions of the prices of domestic availability of the output of each sector, the prices of capital and labor services, and the price of competitive imports for the non-energy sectors. These functions are the relative demand functions of our model of producer behavior; they express the demand for each input relative to the level of output. The level of output of each sector is determined by the composition of final demand. The relative demands for input and the prices of domestic availability of the output of each sector are independent of final demand, depending on y on the prices of the factors of production and the prices of competitive imports for the non-energy sectors.

In implementing an econometric model of producer behavior based on the price possibility frontier our primary objective is to explore the inter-relationships between relative demand for energy and relative demand for capital services, labor services, and non-energy inputs. Similarly, we wish to explore the inter-relationships among relative demands for the five types of energy included in our model -- coal, crude petroleum and natural gas, refined petroleum products, electricity, and gas as a product of gas utilities. We have imposed a structure on the price possibility frontier that permits us to deal with relative demand for energy as a whole and relative demands for the five types of energy included in our model as two separate problems.

To construct a model of the inter-relationship of relative demands for energy, capital services, labor services, and non-energy inputs, we first define groups of inputs that are aggregates of the twelve inputs included in our model of inter-industry production structure. These commodity groups are:

1. Capital (K).
2. Labor (L).
3. Energy (E). This group consists of inputs of coal, crude petroleum and natural gas, refined petroleum products, electricity, and gas as a product of gas utilities.
4. Materials (M). This group consists of inputs of agriculture, manufacturing, transportation, communications, trade and services, and competitive imports for the non-energy sectors.

We first construct a model for producer behavior in terms of the four aggregates -- capital, labor, energy, and materials. We represent the price of domestic availability of the output of each sector as a function of the prices of each of the aggregates. A sufficient condition for the price possibility frontier to be defined on the prices of the four aggregates is that the overall price possibility frontier is separable and homogeneous in the inputs within each aggregate.[17] The price possibility frontier is separable in the commodities within an aggregate if and only if the ratio of the relative shares of any two commodities within an aggregate is independent of the prices of commodities outside the aggregate.[18] For example, the five types of energy make up an appropriate aggregate if the relative value shares of any two types of energy depend only on the prices of energy and not on the prices of non-energy intermediate inputs or the prices of capital and labor services.

The second step in constructing a model of producer behavior is to represent the price possibility frontier for the energy and materials aggregates as functions of the prices of inputs that make up each of the aggregates. For the energy aggregate the price of energy is represented as a function of the prices of the five types of energy that make up the aggregate -- coal, crude petroleum and natural gas, refined petroleum products, electricity, and gas as a product of gas utilities. For the materials aggregate the price of materials is represented as a function of the five types of inputs that make up the aggregate -- agriculture, manufacturing, transportation, communications, trade, and services, and competitive imports for the non-energy sectors.

4.2. Econometric specification. The system of relative demand functions employed in our econometric model of producer behavior for each of the nine industrial sectors of our model is generated from the price possibility frontier for the corresponding sector. For each of the three sub-models that make up our model of producer behavior we represent the price possibility frontier by a function that is quadratic in the logarithms of the prices of the inputs into the sector. The resulting price possibility frontier provides a local second-order approximation to any price possibility frontier. We ferer to our representation as the transcendental logarithmic price possibility frontier or, more simply, the <u>translog price possibility frontier</u>. The price possibility frontier is a transcendental function of the logarithms of the prices of inputs. The translog price possibility frontier was introduced by Christensen, Jorgenson, and Lau.[19]

As an example, the price possibility frontier for the aggregate (KLEM) sub-model takes the form:

$$\ln AI + \ln PI = \alpha^{I}_{0} + \alpha^{I}_{K} \ln PK + \alpha^{I}_{L} + \alpha^{I}_{E} \ln PE + \alpha^{I}_{M} \ln PM$$

$$+ \frac{1}{2} [\beta^{I}_{KK}(\ln PE)^{2} + \beta^{I}_{KL} \ln PK \ln PL + \ldots] \quad ,$$

where PK is the price of capital services, PL the price of labor services, PE the price of energy, and PM the price of materials. For this form of the price possibility frontier, the equations for the relative shares of the four input aggregates take the form:

$$\frac{PK*KI}{PI*XI} = {}^{I}_{K} + {}^{I}_{KK} \ln PK + {}^{I}_{KL} \ln PL + {}^{I}_{KE} \ln PE + {}^{I}_{KM} \ln PM \quad ,$$

$$\frac{PL*LI}{PI*XI} = {}^{I}_{L} + {}^{I}_{LK} \ln PK + {}^{I}_{LL} \ln PL + {}^{I}_{LE} \ln PE + {}^{I}_{LM} \ln PM \quad ,$$

$$\frac{PE*EI}{PI*XI} = {}^{I}_{E} + {}^{I}_{EK} \ln PK + {}^{I}_{EL} \ln PL + {}^{I}_{EE} \ln PE + {}^{I}_{EM} \ln PM \quad ,$$

$$\frac{PM*MI}{PI*XI} = {}^{I}_{M} + {}^{I}_{MK} \ln PK + {}^{I}_{ML} \ln PL + {}^{I}_{ME} \ln PE + {}^{I}_{MM} \ln PM \quad ,$$

$$(I=1,2\ldots9) \quad ,$$

where KI is the quantity of capital services in the Ith sector, LI the quantity of labor services, EI the quantity of energy input, and MI the quantity of materials input.[20]

The dependent variable in each of the four functions generated from the translog price possibility frontier is the relative share of the corresponding input. To derive the input-output coefficient for that input, we divide the relative share by the ratio of the price of the input to the price of the output of the sector. For example, the input-output coefficients for capital services are:

$$\begin{aligned} AKI &= \frac{KI}{XI} \\ &= (\alpha^I_K + \beta^I_{KK} \ln PK + \beta^I_{KL} \ln PL + \beta^I_{KE} \ln PE + \beta^I_{KM} \ln PM)/(PK/PI) \;, \\ &\qquad (I=1,2...9) \;. \end{aligned}$$

Similar expressions can be obtained for the input-output coefficients for labor services, energy, and materials.

The value of domestic availability of the output of each sector is equal to the sum of the values of capital and labor services in that sector and the value of energy and non-energy inputs into the sector:

$$PI*XI = PK*KI + PL*LI + PE*EI + PM*MI \quad , \qquad (I=1,2...9) \;.$$

Given this accounting identify, the relative shares of the four aggregate inputs into each sector add to unity. The parameters of the four relative demand functions for capital and labor services and energy and non-energy inputs must satisfy the restrictions:

$$\alpha_K^I + \alpha_L^I + \alpha_E^I + \alpha_M^I = 1 \quad ,$$

$$\beta_{KK}^I + \beta_{LK}^I + \beta_{EK}^I + \beta_{MK}^I = 0 \quad ,$$

$$\beta_{KL}^I + \beta_{LL}^I + \beta_{EL}^I + \beta_{ML}^I = 0 \quad ,$$

$$\beta_{KE}^I + \beta_{LE}^I + \beta_{EE}^I + \beta_{ME}^I = 0 \quad ,$$

$$\beta_{KM}^I + \beta_{LM}^I + \beta_{EM}^I + \beta_{MM}^I = 0 \quad , \qquad (I=1,2...9) \quad .$$

Given estimates of the parameters of any three equations for the relative shares, estimates of the parameters of the fourth equation can be determined from these restrictions.

The logarithm of the price possibility frontier for each sector is twice differentiable in the logarithms of the prices of inputs, so that the Hessian of this function is symmetric. This gives rise to a set of restrictions relating the parameters of cross partial derivatives. For the aggregate (KLEM) sub-model three of these restrictions are explicit in the three equations we estimate directly, namely:

$$\beta_{KL}^I = \beta_{LK}^I \quad ,$$

$$\beta_{KE}^I = \beta_{EK}^I \quad ,$$

$$\beta_{LE}^I = \beta_{EL}^I \quad , \qquad (I=1,2...9) \quad .$$

In addition, we estimate the parameters β_{MK}^I, β_{ML}^I, and β_{ME}^I (I=1,2...9) from the equations:

$$\beta^I_{MK} = -\beta^I_{KK} - \beta^I_{LK} - \beta^I_{EK} ,$$

$$\beta^I_{ML} = -\beta^I_{KL} - \beta^I_{LL} - \beta^I_{EL} ,$$

$$\beta^I_{ME} = -\beta^I_{KE} - \beta^I_{LE} - \beta^I_{EE} , \qquad (I=1,2...9) ,$$

so that three additional symmetry restrictions are implicit in the equations we estimate, namely:

$$\beta^I_{KM} = \beta^I_{MK} ,$$

$$\beta^I_{LM} = \beta^I_{ML} ,$$

$$\beta^I_{EM} = \beta^I_{ME} , \qquad (I=1,2...9) .$$

For each of the nine industrial sectors, the aggregate (KLEM) sub-model involves six symmetry restrictions.

The price possibility frontier for each sector is homogeneous of degree one; proportional changes in the prices of all inputs result in a proportional change in the price of output. Homogeneity of the price possibility frontier is implied by the symmetry restrictions outlined above and the restrictions implied by the accounting identity between the value of output and the value of input. In the absence of the symmetry restrictions and the restrictions implied by the accounting identity between the value of output and the value of input, the aggregate (KLEM) sub-model involves twenty unknown parameters. Taking these restrictions into account, we reduce the number of unknown parameters to nine.

We have presented the aggregate (KLEM) sub-model of our model of producer behavior in detail. The forms of the energy (E) and Materials (M) sub-models are analogous to the form of the aggregate sub-model. For the energy sub-model we can write the translog price possibility frontier in the form:

$$\begin{aligned} \ln PE = \alpha_0^{EI} &+ \alpha_1^{EI} \ln PE1 + \alpha_2^{EI} \ln PE2 + \alpha_3^{EI} \ln PE3 \\ &+ \alpha_4^{EI} \ln PE4 + \alpha_5^{EI} \ln PE5 \\ &+ \frac{1}{2} [\beta_{11}^{EI} (\ln PE1)^2 + \beta_{12}^{EI} \ln PE1 \ln PE2 + \ldots] \quad , \\ &(I=1,2..9) \quad , \end{aligned}$$

where PE1 is the price of coal, PE2 the price of crude petroleum and natural gas, PE3 the price of refined petroleum products, PE4 the price of electricity, and PE5 the price of gas as a product of gas utilities. Similarly, we can write the translog price possibility frontier for the naterials sub-model in the form:

$$\begin{aligned} \ln PM = \alpha_0^{MI} &+ \alpha_1^{MI} \ln PM1 + \alpha_2^{MI} \ln PM2 + \alpha_3^{MI} \ln PM3 \\ &+ \alpha_4^{MI} \ln PM4 + \alpha_5^{MI} \ln PM5 \\ &+ \frac{1}{2} [\beta_{11}^{EI} (\ln PM1)^2 + \beta_{12}^{EI} \ln PM1 \ln PM2 + \ldots] \quad , \\ &(I=1,2..9) \quad , \end{aligned}$$

where PM1 is the price of agriculture, non-fuel mining, and construction, PM2 the price of manufacturing, excluding petroleum refining, PM3 the price of transportation, PM4 the price of communications, trade and services, and PM5 the price of competitive imports.

For both energy (E) and materials (M) sub-models we can derive a system of five equations for determining the relative shares of the five commodity groups making up each sub-model. Each equation gives the relative share of one of the commodity groups as a function of the prices of all five groups included in the sub-model. We can derive the relative demand functions for each commodity group by dividing the relative value share of the group by the ratio of the price of that group to the price of the corresponding aggregate. For example, to derive the demand for coal relative to total energy we divide the relative value share of coal by the ratio of the price of coal to the price of total energy. We can derive the input-output coefficient for coal by multiplying the demand for coal relative to total energy by the demand for energy relative to the output of the corresponding industrial sector.

The value of each aggregate is equal to the sum of the values of the commodity groups that make up that aggregate. For example, the value of energy is equal to the sum of the values of each of the five types of energy:

$$PE*EI = PE1*E1I + PE2*E2I + PE3*E3I + PE4*E4I + PE5*E5I \quad , \quad (I=1,2,..9) \quad ,$$

where E1I is the quantity of coal, E2I the quantity of crude petroleum and natural gas, E3I the quantity of refined petroleum products, E4I the

the quantity of electricity, and E5I the quantity of gas as a product of gas utilities. As before, the relative shares of the five energy inputs add to unity, so that the parameters of the five relative demand functions for these inputs must satisfy restrictions analogous to the restrictions given above for the parameters of the aggregate (KLEM) sub-model. Similar restrictions hold for the five relative demand functions for non-energy inputs.

4.3. Parameter estimation. For each of the nine industrial sectors included in our inter-industry model of the production structure the aggregate (KLEM) sub-model consists of four equations. We fit the three equations for relative shares of capital (K), labor (L), and energy (E). The relative shares of materials (M) can be determined from these three equations and the accounting identity between the value of output and the value of input. Taking into account the symmetry restrictions on the parameters of the three equations of the aggregate (KLEM) sub-model, the number of unknown parameters to be estimated is reduced to nine. Taking convexity restrictions into account where appropriate, we further reduce the number of unknown parameters.[21]

For four of the industrial sectors included in our inter-industry model the energy (E) sub-model consists of five equations for the relative shares of coal, crude petroleum and natural gas, refined petroleum products, electricity, and gas as a product of gas utilities. These four sectors are:

1. Agriculture, non-fuel mining, and construction.
2. Manufacturing, excluding petroleum refining.

4. Communications, trade, and services.

7. Petroleum refining.

For these industrial sectors we fit the four equations for relative shares of coal, crude petroleum and natural gas, refined petroleum products, and electricity. The relative share of gas as a product of gas utilities can be determined from these four equations and the accounting identity between the total value of energy and the sum of the values of the five types of energy.

For the four industrial sectors listed above the energy (E) sub-model involves six symmetry restrictions in the four equations we estimate directly and four additional restrictions that are implicit in these equations and the accounting identity for the total value of energy. In the absence of these restrictions and the restrictions implied by the accounting identity, the energy (E) sub-model for the four industrial sectors involves thirty unknown parameters. Taking these restrictions into account, we reduce the number of unknown parameters to fourteen.

For four of the industrial sectors included in our inter-industry model the energy (E) sub-model consists of four equations for relative shares of four types of energy. For transportation, coal mining, and electric utilities the relative share of crude petroleum and natural gas is zero. For gas utilities the relative share of electricity is zero. For these four sectors fhe form of the energy (E) sub-model is analogous to the form of the aggregate (KLEM) sub-model. We fit three equations for the relative shares of three types of energy, excluding the equation for the relative share of gas as a product of gas utilities. The relative share of gas can be determined from the accounting identity for the total value of energy. We fit these three equations subject to symmetry restrictions so that the number of unknown parameters is reduced to nine.

For the crude petroleum and natural gas sector of our inter-industry model the energy (E) sub-model consists of three equations for relative shares of three types of energy. For this sector the relative shares of coal and gas as an output of gas utilities are equal to zero. We fit two equations for the relative shares of crude petroleum and natural gas and redined petroleum produtts. The relative share of electricity can be determined from the accounting identity for the total value of energy. Fitting these equations subject to symmetry restrictions, we reduce the number of unknown parameters to five.

For the four non-energy sectors included in our inter-industry model the materials (M) sub-model consists of five equations for the relative shares of agriculture, manufacturing, transportation, communications, and competitive imports. The five energy sectors the materials sub-model consists of four equations for the relative shares of agriculture, manufacturing, transportation, and communications. The form of the materials (M) sub-model for the four non-energy sectors, is analogous to the form of the energy (E) sub-model with five equations for the relative shares of five types of energy. For these sectors we fit four equations for the relative shares of non-energy inputs, exclusing competitive imports. The relative shares of competitive imports can be determined from these four equations and the accounting identity between the total value of materials and the sum of the values of the five types of non-energy inputs. Each of these sub-models involves fourteen unknown parameters.

For the five non-energy sectors we fit ahree equations for the relative shares of non-energy inputs, excluding inputs of communications, trade and services. The materials (M) sub-models for these sectors are analogous to the aggregate (KLEM) sub-model and involve nine unknown parameters.

For each of the nine industrial sectors included in our inter-industry model of production all three sub-models -- aggregate (KLEM), energy (E), and materials (M) -- have been fitted to annual data on inter-industry transactions, capital and labor services, and competitive imports for the period 1947-71.[22] Our method to estimation is the minimum distance estimator for non-linear simultaneous equations, treating the prices of competitive imports as endogenous variables.[23] For each of these sub-models the system of equations is non-linear in the variables but linear in the parameters.

In Tables 4-6 we present estimates of the parameters of the translog price possibility frontier for each of the three sub-models of our econometric model of producer behavior for all nine industrial sectors. The nine industrial sectors are:

1. Agriculture, non-fuel mining, and construction.
2. Manufacturing, excluding petroleum refining.
3. Transportation.
4. Communications, trade, and services; water and sanitary services.
5. Coal mining.
6. Crude petroleum and natural gas.
7. Petroleum refining and related industries.

Table 4. Estimates of the parameters of the translog price possibility frontier for the aggregate (KLEM) sub-model for nine industrial sectors of the U.S. economy, 1947-71.

	Sectors								
Parameter	1	2	3	4	5	6	7	8	9
α_K^I	.1785	.2149	.1798	.2994	.1277	.4272	.1373	.3458	.2165
α_L^I	.2354	.2340	.4096	.4171	.4139	.0987	.0978	.1925	.1085
α_E^I	.0244	.0202	.0380	.0182	.1857	.1101	.4553	.2120	.5547
α_M^I	.5615	.5308	.3726	.2653	.2727	.3640	.3096	.2496	.1204
γ_{KK}^I	.0851	.0590	.1018	.0595	.0280	.2447	.0849	.1330	.0749
γ_{KL}^I	-.0366	.0030	-.0601	.0114	-.0357	-.0422	-.0242	.0288	-.1181
γ_{KE}^I	-.0052	-.0055	-.0137	.0011	.0099	-.0470	-.0772	-.1682	-.0941
γ_{KM}^I	-.0434	-.0565	-.0280	-.0719	-.0022	-.1555	.0165	.0064	.1373
γ_{LL}^I	.0287	.0737	.0582	.0848	-.0751	-.0131	-.0174	-.0968	-.2773
γ_{LE}^I	.0023	.0054	-.0180	.0098	.1145	.0459	-.0122	.0239	.1318

(continued)

Table 4. (concluded)

Parameter	Sectors 1	2	3	4	5	6	7	8	9
γ_{LM}^{I}	.0056	-.0821	.0199	-.1059	-.0037	.0093	.0538	.0441	.2636
γ_{EE}^{I}	.0072	.0188	.0198	.0020	.0087	.0184	.2282	.0638	.1413
γ_{EM}^{I}	-.0044	-.0187	.0119	-.0129	-.1332	-.0173	-.1388	.0805	-.1790
γ_{MM}^{I}	.0422	.1573	-.0038	.1907	.1392	.1635	.0685	-.1311	-.2219

Table 5. Estimates of the parameters of the translog price possibility frontier for the energy (E) sub-model for nine industrial sectors of the U.S., 1947-71.

Parameter	Sectors 1	2	3	4	5	6	7	8	9
α_1^{EI}	.0053	.2040	.0799	.1142	.8510	.0000	.0021	.3165	.0068
α_2^{EI}	.0021	.0002	.0000	.0111	.0000	.8885	.8475	.0000	.3958
α_3^{EI}	.8389	.3384	.8107	.3520	.3997	.0365	.1180	.1173	.0190
α_4^{EI}	.1212	.2858	.0406	.4136	.1062	.0750	.0058	.3829	.0000
α_5^{EI}	.0325	.1716	.0688	.1091	.0029	.0000	.0267	.1829	.5785
β_{11}^{EI}	.0052	.1624	.0735	.1011	-.0118	.0000	.0017	.0762	.0068
β_{12}^{EI}	.0000	.0000	.0000	-.0013	.0000	.0000	-.0095	.0000	-.0027
β_{13}^{EI}	-.068	-.0690	-.0648	-.0402	.0220	.0000	.0067	.0833	-.0001
β_{14}^{EI}	.011	-.0583	-.0032	-.0472	-.0100	.0000	.0009	-.0578	.0000
β_{15}^{EI}	.005	-.0350	-.0055	-.0125	-.0002	.0000	.0003	-.1017	-.0040

(continued)

Table 5. (concluded)

Parameter	Sectors								
	1	2	3	4	5	6	7	8	9
β_{22}^{EI}	.0010	-.0029	.0000	.0110	.0000	.0239	-.0254	.0000	.0557
β_{23}^{EI}	.0007	-.0001	.0000	-.0039	.0000	-.0249	.0388	.0000	-.0075
β_{24}^{EI}	-.0007	.0073	.0000	-.0046	.0000	.0010	.0126	.0000	.0000
β_{25}^{EI}	-.0010	-.0043	.0000	-.0012	.0000	.0000	-.0165	.0000	-.0455
β_{33}^{EI}	-.0252	.2239	.1534	.2281	-.0287	-.0232	-.0206	.0001	.0186
β_{34}^{EI}	.0128	-.0967	-.0329	-.1456	.0064	.0481	-.0164	-.0966	.0000
β_{35}^{EI}	.1854	-.0581	-.0557	-.0384	.0003	.0000	-.0086	.0162	-.0110
β_{44}^{EI}	-.0410	.1868	.0389	.2425	.0055	-.0490	.0038	.2077	.0000
β_{45}^{EI}	.0278	-.0390	-.0028	-.0451	-.0019	.0000	-.0008	-.0502	.0000
β_{55}^{EI}	-.0458	.1364	.0640	.0972	.0018	.0000	.0257	.1357	.0604

Table 6. Estimates of the parameters of the translog price possibility frontier for the materials (M) sub-model for nine industrial sectors of the U.S., 1947-71.

	Sectors								
Parameter	1	2	3	4	5	6	7	8	9
α_1^{MI}	.2578	.1348	.1221	.0819	.0193	.0779	.0562	.1134	.1759
α_2^{MI}	.3777	.5933	.1373	.2548	.4270	.0869	.1656	.1046	.1546
α_3^{MI}	.0653	.0472	.1932	.0532	.0675	.0501	.1736	.1200	.1453
α_4^{MI}	.2674	.1643	.4382	.5774	.4839	.5517	.4659	.6620	.4426
α_5^{MI}	.0318	.0603	.1091	.0327	.0023	.2334	.1388	.0000	.0815
β_{11}^{MI}	.0799	.0376	.1072	-.0454	.0190	.0718	.0530	.0170	-.0407
β_{12}^{MI}	-.1012	-.0200	-.0168	.0848	-.0083	-.0068	-.0093	.0755	.0845
β_{13}^{MI}	.0629	.0043	-.2360	-.0094	-.0013	-.0039	-.0097	-.0292	-.0703
β_{14}^{MI}	-.0672	-.0571	-.0535	-.0806	-.0094	-.0430	-.0262	-.0633	-.0899
β_{15}^{MI}	.0256	.0352	-.0133	.0506	-.0000	-.0182	-.0078	.0000	.1164

(continued)

Table 6. (concluded)

Parameter	Sectors 1	2	3	4	5	6	7	8	9
β_{22}^{MI}	.2349	.1958	.1185	.0973	.2447	.0794	.1382	.0023	-.0070
β_{23}^{MI}	-.0219	-.0361	-.0265	-.0091	-.0288	-.0044	-.0288	.0037	-.0123
β_{24}^{MI}	-.1009	-.0710	-.0602	-.1179	-.2066	-.0480	-.0772	-.0815	-.0895
β_{25}^{MI}	-.0109	-.0687	-.0150	-.0550	-.0010	-.0203	-.0230	.0000	.0243
β_{33}^{MI}	.0039	.0435	.1559	.0502	.0629	.0476	.1434	.1027	.1095
β_{34}^{MI}	-.0187	-.0030	-.0847	-.0321	-.0327	-.0276	-.0809	-.0773	-.0739
β_{35}^{MI}	-.0263	-.0087	-.0211	.0005	-.0002	-.0117	-.0241	.0000	.0471
β_{44}^{MI}	.1959	.1218	.2462	.2348	.2497	.2473	.2488	.2221	.2346
β_{45}^{MI}	-.0090	.0093	-.0478	-.0042	-.0011	-.1287	-.0646	.0000	.0187
β_{55}^{MI}	.0206	.0329	.0972	.0081	.0023	.1789	.1195	.0000	-.2065

8. Electric utilities.
9. Gas utilities.

Table 4 contains estimates of the parameters of the translog price possibility frontier for the aggregate sub-model. The aggregate price possibility frontier is defined on the prices of capital (K), labor (L), energy (E), and materials (M). For each of the nine industrial sectors the parameters of the aggregate sub-model are estimated from a system of three equations. The dependent variables in these equations are the relative shares of capital, labor, and energy in the value of total output. Parameters in the equation for the relative share of materials are estimated from the restrictions implied by the accounting identity between the value of output and the value of input. We employ constraints across the equations arising from symmetry restrictions on the price possibility frontier for each sector, reducing the number of parameters to be estimted to nine. We also employ convexity restrictions, where appropriate, further reducing the number of parameters to be estimated.

Table 5 contains estimates of the parameters of the translog price possibility frontier for the energy (E) sub-model. The energy price possibility frontier gives the price of energy for each sector as a function of the prices of five types of energy inputs. The five types of energy are:

1. Coal.
2. Crude petroleum and natural gas.
3. Refined petroleum products
4. Electricity.
5. Gas as a product of gas utilities.

For each of the nine industrial sectors the parameters of the energy sub-model are estimated from a system containing as many as four equations. The dependent variables in these equations are the relative shares of each type of energy in the total value of energy. We employ the restrictions implied by the accounting identity between the total value of energy and the sum of the values of all types of energy, the symmetry restrictions, and, where appropriate, convexity restrictions in reducing the number of parameters to be estimated.

Finally, Table 6 contains estimates of the parameters of the translog price possibility fuontier for the materials (M) sub-model. For the four non-energy sectors the materials price possibility frontier is defined on the prices of the five types of non-energy inputs. These are:

1. Agriculture, non-fuel mining, and construction.
2. Manufacturing, excluding petroleum refining.
3. Transposration
4. Communications, trade, and services; water and sanitary services.
5. Competitive imports.

For the five energy sectors the materials price possibility frontier is defined on the prices of four types of non-energy inputs, excluding competitive imports. The dependent variables are relative shares of each type of non-energy input. We employ restrictions on the parameters that are analogous to the restrictions used for the energy sub-model.

5. Energy Projections.

5.1. Introduction. Our next objective is to provide a reference point for the analysis of energy policy by establishing detailed projections of energy demand and supply, energy price and cost, and energy imports and exports. We have attempted to implement this objective within a framework that incorporates the determinants of both demand and supply for energy in the U.S. economy. The first component of this framework is our macro-economic growth model, which includes production and household sectors of the U.S. economy as endogenous sectors and exogenous foreign and government sectors. The second component of the framework is an inter-industry model, incorporating transactions between producers of energy and ultimate consumers and also transactions among the producing sectors for both energy and non-energy products.

The actual solution of our complete model proceeds along the following lines: First, our macro-econometric growth model is used to obtain projections of aggregate consumption, investment and government final demand and the price of labor and capital services. Second, we calculate the prices of final products corresponding to prices of primary inputs and competitive imports and to levels of technology in each of the producing sectors. Third, we disaggregate final demand totals into final demand for the output of each of the producing sectors. Fourth, models of producer behavior are used to calculate the input-output coefficients specifying the patterns of input into each of the nine producing sectors. Finally, the final demand requirements for each sector are combined with the input-output coefficients to obtain the total output of each sector as well as sales to other producers and final users. Output requirements are translated into requirements for capital and labor input and levels of competitive imports.

We first present detailed projections for the year 1980 under the assumption of no change in energy policy. These projections can be compared with inter-industry transactions for 1970 presented above in Section 3. Next, we translate energy flows for coal, refined petroleum products, electricity, and gas--the products of four of the nine sectors included in our inter-industry model--into physical units. These flows are given in trillions of Btu's for 1970, 1975, 1980, 1985 and 2000. The resulting energy flows provide the information required to translate our detailed inter-industry projections into the energy balance framework that has become conventional in the analysis of patterns of energy utilization.[24]

Our inter-industry approach to the projection of patterns of energy utilization imposes the same consistency requirements as the energy balance approach, namely, that demand is equal to supply for each type of energy. In addition, our approach requires that demand and supply are consistent with the same structure of energy prices and that markets clear at these prices. The final step in our analysis is to present our results in the form of energy balance tables. We then compare our projections with conventional energy balance projections. Our results suggest that energy blaance projections should be integrated with projections of the future development of energy prices. Our inter-industry framework provides a means of combining projections of energy flows and energy prices.

5.2. Inter-industry transactions. For comparison with energy balance projects we find it useful to translate inter-industry flows for energy products into physical units.[25] For 1970 and 1980 inter-industry flows of energy can be obtained from the inter-industry transactions in constant prices. For coal products we convert the constant dollar flows for Sector 5 of our inter-industry model into Btu's in Table 7. Domestic output must be added to imports

Table 7: Coal Demand and Supply

(Energy flows in trillion Btu)

	Supply			Demand Energy use by sectors:													
	Domestic Output	Imports	Total Supply	1	2	3	4	5	6	7	8	9	10	11	12	13	Total Demand
1970	12920	0	12922	17	2095	9	276	767	0	11	7483	4	109	99	23	1991	10931
1975	15680	17	15697	33	3598	155	1476	1055	0	40	7258	56	57	2	13	1955	13742
1980	18728	21	18749	40	4464	181	1862	1380	0	52	8167	454	70	2	16	2061	16688
1985	23596	26	23622	56	6029	230	2257	2067	0	67	8388	2073	91	3	21	2401	21221
2000	35646	17	35663	74	8892	277	2687	3812	0	94	9546	7163	99	3	23	2975	32688

to obtain total supply. Supply is allocated among intermediate and final demand, just as in our inter-industry transactions tables. We also present inter-industry flows of coal for 1975, 1985 and 2000 in Table 7. These flows were projected in precisely the same way as the flows for 1980 given in Table 7.

For refined petroleum products we convert the constant dollar flows for Sector 7 of our inter-industry model into Btu's in Table 8. We add domestic output of refined petroleum products to imports to obtain total supply. We find it convenient to include imports of crude petroleum in this table. Total supply is allocated among intermediate and final demand categories. Similarly, we present inter-industry flows of electricity in Btu's in Table 9 and inter-industry flows of natural gas in Table 10. For Tables 18-20 we present actual flows for 1970 and projected flows for 1975, 1980, 1985, and 2000. All of these energy flows are obtained from the corresponding constant dollars flows by conversion to physical units.

5.3. Energy balance. Our projections include total production and total domestic utilization of coal, crude petroleum and natural gas, refined petroleum products, electricity, and gas as a product of gas utilities. We also project prices for each type of energy. We allocate energy utilization between intermediate and final demand. Finally, we allocate intermediate demand among the nine producing sectors of our model, including the energy producing sectors and agriculture, manufacturing, transportation, and trade and services. We allocate final demand among the four consuming sectors--personal consumption, investment, government consumption, and exports. The distinction between intermediate and final demand has no counterpart in energy balance projections, but these categories must be distinguished in order to integrate energy utilization into the framework provided by the U.S. national income and product accounts.

Table 8: Refined Petroleum Products Demand and Supply

(Energy flows in trillion Btu)

Supply					Demand Energy use by sectors:													
	Domestic Output	Imports of Crude	Imports of Refined	Total Supply	1	2	3	4	5	6	7	8	9	10	11	12	13	Total Demand
1970	24942	2716	4672	29614	3581	3845	1745	4557	26	77	2187	2087	69	10270	85	917	519	29095
1975	27269	5339	7626	34895	3490	3866	2387	4309	207	32	2108	2161	136	14181	76	1288	654	34241
1980	31275	7587	10833	42108	4153	4609	2848	5374	266	43	2490	2672	573	16685	88	1558	547	41561
1985	32454	9034	18067	50521	5336	5760	3506	6812	378	64	2881	2112	810	20329	110	1940	483	50038
2000	46553	10237	25594	72147	7175	6360	5103	15624	1210	126	3985	4305	709	23965	174	3097	315	71832

Table 9. Electricity Demand and Supply

(Energy flows in trillion Btu)

	Supply			Demand Energy use by sectors:													
	Domestic Output	Imports	Total Supply	1	2	3	4	5	6	7	8	9	10	11	12	13	Total Demand
1970	5220	0	5220	115	912	16	1637	12	29	36	506	0	1862	0	94	2	5218
1975	7280	0	7280	355	1084	27	1916	89	52	30	615	0	2875	0	231	5	7275
1980	10231	0	10231	500	1264	35	2850	107	56	35	715	0	4311	0	352	5	10226
1985	13956	0	13956	559	1569	45	4112	234	59	39	709	0	6174	0	550	6	13950
2000	30404	0	30404	1012	2720	68	8303	283	52	46	910	0	15478	0	1527	7	30377

Table 10. Gas Demand and Supply

(Energy flows in trillion Btu)

Supply				Demand Energy use by sectors:													
	Domestic Output	Imports	Total Supply	1	2	3	4	5	6	7	8	9	10	11	12	13	Total Demand
1970	21183	846	22029	186	2904	183	1253	2	0	446	4015	6888	5621	0	487	72	21957
1975	22501	2580	25081	298	3182	219	1507	14	0	534	3852	7512	7077	0	797	89	24992
1980	24264	4020	28284	293	3519	289	2527	17	0	648	4346	7585	8050	0	934	76	28208
1985	25185	5880	31065	416	4322	360	2830	21	0	751	4862	7723	8555	0	1157	68	30997
2000	28482	11130	39612	845	4079	535	4203	44	0	1179	5949	8827	12088	0	1824	39	39573

Our projections of inter-industry transactions are summarized in Table 11, which gives the average growth rates of sector sales, production and prices. All sectors show sales growth in the rate 6% to 9% a year with agricultural, services, coal and electricity sectors showing above average growth rates. But, when allowance is taken of price increases, the spread in growth rates of real output becomes more pronounced, ranging from a low of 1.8% a year for gas utilities to 5.9% for electricity. Output from the agriculture, services, coal, crude petroleum, refined petroleum and gas utility sectors can be seen to be increasing more slowly than the overall sector average. Correspondingly, agriculture, services, coal, refined petroleum and gas prices increase more rapidly than average.

Our projection of total U.S. energy utilization for the period 1975-2000 is given in Table 12. Total U.S. energy consumption is forecast to increase from 80,250 trillion Btu in 1975 to 174,470 trillion Btu in 2000, an average annual growth rate of 3.2%. Within this total, a significant shift towards more secondary forms of energy consumption (principally electricity) is expected. Coal usage grows in line with total energy consumption as coal becomes increasingly important as a source of synthetic gas and as an input to electricity generation. Petroleum gradually declines in relative importance as an energy source--consumption of refined petroleum is forecast to increase at 2.9% compared to the 3.2% growth of total energy consumption--but petroleum still accounts for 41% of energy consumption in 2000. Electricity usage increases much more rapidly, at a 5.9% annual rate, than total energy consumption, increasing its share of energy consumption from 9% in 1975 to 17% by 2000. Gas, on the other hand, declines in relative importance from 31% of total energy consumption in 1975 to 23% in 2000, corresponding to an average growth rate of only 1.8% per annum.

Table 11. Transactions Summary, 1975-2000.

(average annual percentage growth rates, 1975-2000.)

Sector	Total sector output in current dollars	Total sector output in constant (1971) dollars	Price of sector output
1. Agriculture	7.4	2.4	4.9
2. Manufacturing	7.0	3.5	3.4
3. Transportation	6.5	4.1	2.3
4. Trade and Services	7.4	3.2	4.1
5. Coal	8.9	3.3	5.4
6. Crude Petroleum	6.4	3.1	3.2
7. Refined Petroleum	7.0	3.0	4.0
8. Electricity	7.6	5.9	1.6
9. Gas Utilities	6.1	1.8	4.2

Table 12. Total U.S. Energy Utilization, 1970-2000.

	1970	1975	1980	1985	2000
Coal					
Use (Tr.Btu)	10931	13742	16688	21221	32688
% of total	16.3	17.1	17.3	18.3	18.7
Average growth rate (% a year)		4.7	4.0	4.9	2.9
Petroleum					
Use (Tr.Btu)	29295	34241	41561	50038	71832
% of total	43.3	42.4	43.0	43.1	41.2
Average growth rate		3.3	4.0	3.8	2.4
Electricity					
Use (Tr.Btu)	5218	7275	10226	18950	30377
% of total	7.8	9.1	10.6	12.0	17.4
Average growth rate		6.9	7.1	6.4	5.3
Gas					
Use (Tr.Btu)	21957	24992	28208	30997	39573
% of total	32.7	31.1	29.2	26.7	22.7
Average growth rate		2.6	2.5	1.9	1.6
Total					
Use (Tr.Btu)	67201	80250	96683	116206	174470
% of total	100.0	100.0	100.0	100.0	100.0
Average growth rate		3.6	3.8	3.7	2.7

Coal continues to be a major energy source in the U.S. economy. Although it supplies virtually no final demand it retains its importance as a primary energy source to industry and to secondary energy generation. On the supply side, domestic production continues to supply virtually all coal requirements; on the demand side, coal is used primarily as a fuel for manufacturing industry and as an input into the electricity generation and gas utility sectors. Although current use of coal by gas utilities is negligible, this is expected to change with the development and introduciton of synthetic gas production using coal and petroleum as fuel inputs. Also, coal is expected to remain an important export commodity. The utilization of coal for the period 1970-2000 is summarized in Table 13.

Utilization of petroleum products is projected to show similar growth in both intermediate and final demand categories On the supply side, imports contribute an increasing share of total supply, although, in the latter years of the forecast period, the introduction of shale oil is expected to lessen the dependence on imports. On the demand side, the services sector is forecast to rapidly increase its consumption of petroleum and, by 2000, to become the largest intermediate user. Personal consumption use of petroleum also increases steadily, remaining the largest single consumption category.

Demand by all sectors for electricity, both intermediate and final, is expected to increase rapidly. Personal consumption use of electricity continues to dominate consumption but use as an intermediate input, particularly into the service sector, is also very important. Gas, as a product of gas utilities, declines in relative importance. Imports are projected to provide an increasing proportion of gas supply. In addition, synthetic gas produced from coal and petroleum is expected to become significant in the 1980's and, by 2000,

Table 13. Energy Utilization Summary

	USAGE (Trillion Btu)			GROWTH RATES (Average percent per annum)		
	Final Consumption	Interindustry use	U.S. demand	Final Consumption	Interindustry use	U.S. demand
Coal						
1970	231	10700	10931			
1975	72	13670	13742	-20.8	5.0	4.7
1980	88	16600	16688	4.1	4.0	4.0
1985	115	21106	21221	5.5	4.9	4.9
2000	125	32563	32688	0.6	2.9	2.9
Refined Petroleum						
1970	11272	17823	29095			
1975	15545	18696	34241	6.6	1.0	3.3
1980	18531	23030	41561	3.6	4.3	4.0
1985	22379	27659	50038	3.8	3.7	3.8
2000	27236	44596	71832	1.3	3.2	2.4
Electricity						
1970	1956	3262	5218			
1975	3106	4169	7275	9.7	5.0	6.9
1980	4663	5563	10226	8.5	5.9	7.1
1985	6724	7226	13950	7.6	5.4	6.4
2000	17005	13372	30377	6.4	4.2	5.3
Gas						
1970	6108	15849	21957			
1975	7874	17118	24992	5.2	1.6	2.6
1980	8984	19224	28208	2.7	2.3	2.5
1985	9712	21285	20997	1.6	2.1	1.9
2000	2000	13912	25661	2.4	1.3	1.6

to provide 14% of total gas supply. Projections of synthetic fuel production are given in Table 14. All sectoral demands for gas increase but personal consumption continues to be the principal usage while manufacturing, services, electricity generation and the gas utility sector itself are the main intermediate users.

The first comparison between our projections and energy balance projections is between the projections we have given in Tables 1, 2 and 12 and corresponding projections for 1975 and 1985 prepared by the Committee on the U.S. Energy Outlook of the National Petroleum Council.[26] The projections of domestic utilization of energy by the National Petroleum Council are given in Table 15 for coal, oil, and gas. These projections can be compared with our projections for coal, refined petroleum products, and gas as a product of gas utilities. The percentage increase in fossil fuel utilization over the period 1970 to 1975 is almost identical for the two sets of projections. For the period 1975-1985 our projection of fossil fuel utilization is above that of the National Petroleum Council. This difference is due to the greater role assigned to nuclear generation of electricity in the National Petroleum Council estimates. The use of primary energy sources is approximately the same in the two projections.

A critical element in any set of energy projections is the projection of electricity demand. A detailed comparison of alternative electricity demand projections has been made by Chapman, Mount, and Tyrrell.[27] A summary of their results is given in Table 16 for the years 1970-2000. The first three rows summarize alternative "high" growth projections of electricity demand by the National Petroleum Council (NPC), the 1970 National Power Survey of the Federal Power Commission (FPC), and the Cornell University-National Science Foundation

Table 14. Supplemental Energy Supplies
(Energy flows in trillion Btu)

IMPORTS

	Petroleum				Natural Gas	
	Crude	Refined	Total	% U.S. Demand	Total	% U.S. Demand
1970	2716	4627	7388	25	846	4
1975	5339	7626	12965	37	2580	10
1980	7587	10833	18420	44	4020	14
1985	9034	18067	27100	54	5880	19
2000	10237	25594	35831	50	11130	28

SYNTHETIC FUEL

	Gas				Oil	
	Coal input	Petroleum input	Output	% U.S. Demand	Total*	% U.S. Demand
1970	-	-	-	-	-	-
1975	-	-	-	-	-	-
1980	430	440	700	2	-	-
1985	2000	670	2000	6	-	-
2000	7140	550	5500	14	14330	20

* This refers to oil produced from shale. It is possible that small quantities of oil will be produced by coal liquifaction but this is not included.

Source: Based on the import and synthetic fuel assumptions made by Dupree and West, (1973).

Table 15. U.S. domestic utilization of fossil fuels, 1970-1985, projections by the National Petroleum Council, annual growth rates.

Energy source	Time interal	NPC projection	HJ projection
Coal	1970-1975	4.5	13.1
	1975-1985	3.5	2.6
Oil	1970-1975	6.1	2.5
	1975-1985	3.5	4.4
Gas	1970-1975	-0.7	2.0
	1975-1985	-0.1	4.7

Sources: NPC: National Petroleum Council (1971) Table II, page 13. Annual growth rates computed from original data given in trillion btu's.

HJ: Our projection.

Table 16. U.S. domestic utilization of electricity, 1970-2000, alternative projections, trillion kilowatt hours.

Projection	1970	1975	1980	1985	1990	2000
NPC	1.59	2.29	3.29	4.54	--	--
FPC	1.53	--	3.07	--	5.83	--
Cornell-NSF	1.57	2.15	2.92	3.96	5.38	10.25
CMT - High	1.53	2.14	3.05	--	5.66	9.89
- Medium	1.53	1.98	2.38	--	3.01	3.45
- Low	1.53	1.88	2.07	--	2.11	2.01
HJ	1.53	1.88	--	3.62	--	9.40

Sources: NPC (National Petroleum Council), FPC (Federal Power Commission), Cornell-NSF (Cornell-National Science Foundation Workshop): Chapman, Mount, Tyrrell, (1972), Table 1, page 3.

CMT: Chapman, Mount and Tyrrell, (1972), table 2, page 15, BEA population assumption, "High" corresponds to the real price of electricity doubling by the year 2000; "Medium" corresponds to the Federal Power Commission estimate of a 19 per cent real price increase from 1970-1990; "Low" corresponds to a decline of the real price by 24 per cent from 1970-1980 and 12 per cent from 1980-1990 and 1990-2000.

HJ: Our projection.

Workshop (Cornell-NSF). The second three rows summarize alternative projections by Chapman, Mount, and Tyrrell, based on an econometric model of energy demand that incorporates the effect of electricity prices, population, income, and natural gas prices.

Chapman, Mount, and Tyrrell present projections of electricity demand based on alternative assumptions about the growth of the price of electricity and the growth of population. We have limited our summary of their results to projections based on the same population projections employed in our own work. These population projections are the Census D Projections, which imply that population growth will continue at a positive rate for the foreseeable future. The "high" projections of electricity demand given in Table 16 are based on a falling price of electricity relative to the consumer price index. The "medium" and "low" projections are based on alternative rates of increase in the price of electricity relative to the consumer price index. The "medium" projections are based on an increase in the electriicty relative to the consumer price index of 19 percent over the period 1970-1990. The "low" projections are based on a doubling of this price ratio over the period 1970-2000.

Except for 1975 our projections of electricity utilization in the United States coincide with the "high" projections of Chapman, Mount, and Tyrrell. We project a decline in the ratio of the price of electricity to the price of personal consumption expenditures. The basis for this projection is that the important inputs of the electric generating sector--capital services and fuel--do not increase in price relative to the price of personal consumption expenditures, while productivity growth in this industry continues to be unusually rapid. A dramatic increase in capital costs due to regulations requiring environmental protection, not incorporated into our present forecasts of

Table 17. U.S. domestic utilization of fossil fuels for generation of electricity, 1970-1985, projections by National Economic Research Associates and National Petroleum Council, annual growth rates.

Energy source	NERA projection	NPC projection	HJ projection
Coal	2.7	4.1	-0.3
Oil	0.2	4.6	1.4
Gas	3.5	0.0	4.6

Sources: NERA: National Economic Research Associates, Inc., (1972) Table 13, page 28. Annual growth rates computed from original data given in short tons for coal, barrels of oil, and thousands of cubic feet for gas.

NPC: National Petroleum Council (1972), page 20. Annual growth rates computed from original data given in btu's.

HJ: Our projection.

productivity growth in the electric generating industry, would counteract this trend. Sufficiently high costs of environmental protection or changes in taxation would result in electricity utilization estimates in the "medium" or "low" range suggested by Chapman, Mount and Tyrrell.

The final comparison between our projections and alternative projections is for projected rates of growth of fossil fuel utilization for the generation of electricity in the United States. Projections for 1970 and 1985 by National Economic Research Associates for the Edison Electric Institute and by the National Petroleum Council are given in Table 17.[28] Both alternative projections are based on demand for electricity from the 1970 National Power Survey.[29] Our projections of natural gas used in the generation of electriicty are higher than either of the alternative projections. Our projections of oil used are above those of National Economic Research Associates and below those of the National Petroleum Council. Finally, our projections of coal use are below both alternative sets of projections. An examination of our projections of price trends for the three fuels provides an explanation for our results. We project an increase in the price of coal relative to the prices of the other two energy sources. We project a fall in the price of oil relative to the prices of gas and coal. A very sharp rise in gas prices would be required to bring our estimates of gas used by electric utilities into line with the projections of the National Petroleum Council.

Except for the projections of electricity demand by Chapman, Mount, and Tyrrell, the projections of energy utilization we have reviewed have been prepared without explicit assumptions about the growth of energy prices relative to other prices or about the relative growth of the prices of alternative fuels. Our projections include projections of energy demand and supply, energy price and cost, and energy imports and exports. The implications of alternative assumptions about the determinants of energy demand and supply, for example, assumptions about population growth or productivity change, can be determined for both the overall growth of energy utilization and the distribution of energy growth among alternative energy sources. We can determine the direct effects of facto affecting demand or supply for a given energy source on the utilization and price of that source. We can also determine the impact of these factors on the utilization and price of alternative energy sources.

Our projections have been prepared as a reference point for the analysis of energy policy. In making these projections we have assumed no change in energy policy. Although our projections differ in detail from projections based on the energy balance approach, the overall pattern of our projections is similar to the pattern suggested by "high growth" projections, such as the projections of the National Petroleum Council, the Federal Power Commission, and National Economic Research Associates. Our projections of the growth of electricity demand are comparable to the highest projections presented by Chapman, Mount, and Tyrrell. Our price projections for electricity are consistent with the price projections that underly the highest demand projections given by Chapman, Mount and Tyrrell.

6. Energy Policy.

6.1. Introduction. Our detailed projections of energy demand and supply for the period 1975-2000 are intended to serve as a reference point for policy analysis. These projections embody no major new departures in energy policy. To analyze the effect of a given change in energy policy our methodology is to prepare an alternative set of projections, incorporating the policy change, and to compare the resulting balance of energy demand and supply with the balance under no change in policy. To illustrate our methodology we present a detailed analysis of a uniform rate of tax per Btu for each type of energy used in the U.S. economy, as proposed in The Energy Revenue and Development Act of 1973, introduced by Senator Mike Gravel and the subject of recent hearings by the Senate Finance Committee.[30]

We can distinguish between two types of Btu taxes, first, a uniform tax on all energy consumed and, second, a uniform tax on final consumption of energy. A tax on all energy consumed would have the effect of creating a wedge equal to the tax rate between the price received by an energy producer and the price paid by an energy consumer. The first stage of our policy analysis is to re-compute the prices for all nine sectors of the U.S. economy, incorporating the taxes paid by consumers into our behavioral equations for the demand and supply for energy. Given the resulting prices, we then determine the corresponding input-output coefficients for all sectors. Finally, we estimate the effect of the change in prices on the allocation of personal consumption expenditures to obtain the component of the final demand vector corresponding to personal consumption expenditures.

The final stage of our analysis is to determine the effects of a uniform Btu tax on all energy consumed on industry output levels and on the allocation of employment and capital among sectors by means of input-output analysis, based on the new set of input-output coefficients. These effects include the direct effects of the substitution of capital and other inputs for energy in the producing sectors and the indirect effects induced by changes in the relative prices of all products as a result of the tax on energy. Given the levels of domestic production of each type of energy and the prices of energy products, we can determine the impact of the Btu tax on the level of energy imports and the balance of trade of the U.S. economy.

A uniform Btu tax on final consumption of energy has fewer repercussions than a tax on all energy consumed. Given the prices of energy and other products, a tax on the final consumption of energy creates a wedge between the prices paid for energy by producers and prices paid by final consumers. Given the prices of energy, including the tax, and the prices of other products in the economy, we can determine the allocation of personal consumption expenditures among the eleven components included in our model of the household sector. We replace the consumption component of final demand by the new consumption vector and re-compute industry output levels, employment, and the distribution of capital among sectors. As before, we can determine the impact of the tax on energy imports and the balance of trade.

We first present a summary of the impact of a Btu tax on total energy consumption in the new consumption in the United States and on the composition of energy utilization. We attempt to answer the following questions:

1. What effect does a Btu tax have on energy use?
2. How does this effect vary with the tax rate?
3. Does the effect differ between intermediate and final energy use?
4. What is the effect of a Btu tax levied only on intermediate energy use?

5. What is the effect of a Btu tax levied only on final energy use?

We next consider possible tax policies in which the Btu tax can be used to achieve the goal of independence from energy imports by 1985. Of course, the Btu tax is only one of many policy instruments that might be used to reduce demand such as a sales tax on energy, tax incentives or direct subsidies to stimulate supply, government research and development programs to stimulate the introduction of new energy technologies, energy conservation measures such as restrictions on the use of passenger automobiles, and so on. Our conclusion is that independence of energy imports can be achieved by tax policy, but that the tax rates required increase rapidly with time. For example, energy independence requires a tax rate of 29 cents per million Btu in 1980, but the required tax rate rises to 64 cents per million Btu in 1985.

6.2. Tax policy and conservation. The simulations involving the Btu tax in this section were conducted under the assumption that the tax is not accompanied by any change in import regulations so that just as much energy can be imported once the tax is imposed as in the absence of the tax. The impact of various levels of Btu tax on intermediate, final and total energy demand is shown in Table 18. The results in this table suggest the following conclusions. First, the Btu tax can produce a significant reduction in total energy use. The highest rate shown, $190,000 per trillion Btu, induces a 15.6% reduction in energy demand. Reductions of this order, as will be discussed in the next section, are sufficient to achieve U.S. energy independence by the early 1980's. Second, the incremental impact on energy use of the Btu tax diminishes as the tax increases. Thus, while the lowest tax shown leads to a reduction of 72.4 quadrillion Btu's for each million dollars per trillion Btu, this reduction steadily falls to 65.8 quadrillion Btu per million dollars of

Table 18.

Impact of Btu Taxes on Energy Use in 1975*

Tax Rate ($m/tr Btu)	0	0.0575	0.077	0.119	0.190
Total U.S. Energy Use					
Use (tr Btu)	80250	76085	74755	72018	67755
Change in use (tr Btu)		4165	5495	8232	12495
Change/tax rate		72434	71363	69176	65763
Percentage reduction in use		-5.2	-6.8	-10.3	-15.6
Intermediate Energy Use					
Use (tr Btu)	53657	51299	50535	48948	46436
Change in use (tr Btu)		2358	3122	4709	7221
Change/tax rate		41008	40545	39571	38005
Percentage reduction in use		-4.4	-5.8	-8.8	-13.5
Final Energy Demand					
Use (tr Btu)	26593	24787	24220	23070	21320
Change in use (tr Btu)		1806	2373	3523	5273
Change/tax rate		31408	30818	29605	27752
Percentage reduction in use		-6.8	-8.9	-13.2	-19.8

* This refers to a Btu tax applied to all energy sales. No change in import regulations is assumed. The 1975 forecast is that shown in Section 2.

tax for the highest tax rate shown. It is also the case, however, that this reduction is rather gradual so that an assumption of constant tax effectiveness is not, as a first approximation, unreasonable. Third, the impact of the tax is proportionately greater for final demand than for intermediate demand for energy. Typically, the percentage reduction in energy use for intermediate purposes is only two thirds the reduction in final demand use. The absolute reduction in energy usage is, however, greater in intermediate than in final demand categories. Thus, it turns out that the Btu tax leads to more Btu's being released from intermediate use than from final use although it is the final users who give up relatively more of their consumption.

The Btu tax rates are translated into dollars per physical unit of each fuel in Table 19. The taxes are around $2 per ton of coal, about one fourth its average 1971 price, around $0.40 a barrel of oil, less than ten percent of its average price, around $0.0003 a kilowatt hour of electricity, only about 2% of the electricity price, and around $0.10 per thousand cubic feet of gas, about one-tenth of the gas price. The different ratios of tax to fuel price primarily reflect the different Btu contents per dollar of each fuel--coal is by far the cheapest fuel in terms of Btu cost and consequently, the Btu tax forms a much larger sum in relation to its price than in the case of the other fuels, while electricity is very expensive per Btu so that the Btu tax is very small in relation to the price.

The impact of a tax on any fuel varies according to the tax base, in particular as to whether it is levied on final uses of energy, on intermediate uses or on both. The impact of a Btu tax applying to all energy sales has been summarized above. We now compare the impact of the Btu tax when the base is restricted first to intermediate purchases of energy and second to purchases of energy for final use. Table 20 presents the energy consumption in each of these

Table 19.

Btu Tax Rates in Terms of Physical Units

Btu Tax Rate ($m/tr Btu)	0.0575	0.077	0.119	0.190	Average 1971 Price
	Equivalent tax per physical unit				
Coal $/short ton	1.41	1.89	2.93	4.67	8.35
Refined petroleum products, $/barrel	0.32	0.42	0.66	1.05	6.49
Electricity $/kwhr	0.0002	0.0003	0.0004	0.0007	0.017
Gas $/thousand cubic feet	0.06	0.08	0.12	0.20	0.91

Table 20.

Impact of Btu Taxes Applied to Different Bases *

	Only Final Energy Sales Taxed				Only Intermediate Energy Sales Taxed			
Tax Rate $m/tr Btu	0	0.077	0.119	0.190	0	0.077	0.119	0.190
Total U.S. Energy Use								
Use (tr Btu)	80250	77988	76880	75177	80250	76907	75142	72261
Change in use (tr Btu)		2262	3370	5073		3343	5108	7989
Change/tax rate		29376	28319	26700		43415	42924	42047
% reductions in use		-2.8	-4.2	-6.3		-4.2	-6.4	-10.0
Intermediate Energy Use								
Use (tr Btu)	53657	52980	52649	52141	53657	51158	49837	47682
Change in use (tr Btu)		677	1008	1516		2499	3820	5975
Change/tax rate		8792	8470	7979		32454	32100	31447
% reductions in use		-1.3	-1.9	-2.8		-4.7	-7.1	-11.1
Final Energy Demand								
Use (tr Btu)	26593	25008	24231	23036	26593	25749	25305	24580
Change in use (tr Btu)		1585	2362	3557		844	1288	2013
Change/tax rate		20584	19848	18721		10961	10823	10594
% reduction in use		-6.0	-8.9	-13.4		-3.2	-4.8	-7.6

* The simulations are based on the 1975 forecast described above.

cases for three of the tax rates considered above.

The results emerging from Table 20 can be summarized as follows. First, a tax only on intermediate energy sales induces a greater reduction in actual energy consumed than does the same rate of tax applied only to final sales. Second, either tax base offers the potential for significant reductions in total energy use. Thus if political considerations dictated that only final energy sales be taxed, the Btu tax could still cause marked reductions in total energy use. Third, even if a tax is levied only on one class of sale, the other class is still affected. Tax on final use leads to a reduction in final energy use which, in turn, leads to reduced activity in the fuel sectors and to reduced intermediate purchases by these sectors. Similarly, a tax only on intermediate energy use leads to increased fuel prices and these lead to decreased energy use at final as well as intermediate levels of activity. It does emerge, however, that the tax on final use has less impact on intermediate energy consumption than the tax on intermediate consumption has on final energy use.

6.3. Import independence. This section examines various tax scenarios in which the Btu tax can be used to achieve the goal of independence from energy imports by 1985. Again, the analysis is based on the DRI energy model so that account is taken of final demand, intermediate demand, and input substitution effects on the tax. Also, it must be emphasized that the Btu tax is only one of several policy instruments that are available to the U.S. government in reducing consumption of, and imports of, energy; another possible tax, the sales tax on energy, is discussed in the following section.

Table 21 shows, for the three forecast years 1975, 1980 and 1985, the impact of several Btu taxes on total U.S. energy demand and on U.S. imports of energy. The Btu tax is applied uniformly to all fuel imports and to domestic sales of

Table 21

Impact of Various Btu Taxes on U.S. Energy Demand

			1975				1980			1985	
Tax Rate ($/m Btu)	0	0.0575	0.077	0.119	0.190	0	0.184	0.290	0	0.480	0.640
Total U.S. Energy Demand (tr Btu)	80250	76319	75062	72468	68405	96684	85405	79856	116207	91140	84622
Change in Total Demand from Base Case (%)	0	-4.9	-6.5	-9.7	-14.8	0	-11.7	-17.4	0	-21.6	-27.2
Imports of Energy (tr Btu)	15557	11670	10375	7783	3896	22454	11232	5620	32998	8256	1659
Change in Imports from Base Case (%)	0	-25.0	-33.3	-50.0	-75.0	0	-50.0	-75.0	0	-75.0	-95.0
Imports in Total Demand (%)	19.4	15.3	13.8	10.7	5.7	23.2	13.2	7.0	28.3	9.1	2.0
Tax Revenue ($bn)	0	4.388	5.779	8.623	12.996	0	15.714	23.158	0	43.747	54.158

coal, crude petroleum, refined petroleum products, electricity and natural gas. The simulations assume that, since import independence is the policy objective, reductions in energy usage induced by the tax are translated by import regulation into a reduction in imports. Although only oil and gas supplies are directly affected by this import reduction, the price effects of the tax, along with the lower import levels, operate through interindustry dependence and energy substitutions to produce changes in use of all types of energy. These detailed effects are examined below. Four different tax rates are shown for 1975 to illustrate the relation between tax rate and energy use; in 1980 and 1985 only two tax rates are shown.

The results shown in Table 21 show that the Btu tax can be an effective means of reducing use of energy. The taxes shown reduce demand by up to 27%; higher taxes would result in still greater reductions. But, more important, the Btu tax is an effective means of reducing dependence on imports. The 1985 simulations show that a progressive increase in the Btu tax rate to $0.640 per million Btu will serve to reduce imports to a negligible level (a level equal to about one tenth of 1973 imports). It can be seen that there are various ways of increasing the tax rate over the period up to 1985 that will secure this goal of energy independence. For example, one possible tax scheme that would secure import independence is shown in Table 22, but this is only one of many possible systems that can be inferred from Table 21. The tax cannot be removed after 1985, however. In fact, the tax rate will have to increase gradually from its 1985 level if demand is to be maintained at a level that can be satisfied from U.S. production with only minimal energy imports.

The Btu tax required to achieve energy independence by 1985 would produce substantial revenue for the Federal Government. Table 21 shows estimates

Table 22.

A Possible Btu Tax System for Energy Independence

	Tax Rate ($/m Btu)	Imports in U.S. Energy Use (%)
1975	0.0575	15.3
1976	0.0795	
1977	0.110	
1978	0.152	
1979	0.210	
1980	0.290	7.0
1981	0.340	
1982	0.400	
1983	0.466	
1984	0.546	
1985	0.640	2.0

of this revenue which would start in the region of $4 bn in 1975 and increase up to $54 bn by 1985. This revenue would be sufficient to sustain a substantial Energy Trust Fund which could, in turn, be used to support large-scale energy research and development. Alternatively, or in addition, these funds could be used to support the extended mass transit facilities that would be necessary as people were induced by the energy tax to place less reliance on the automobile for urban transportation. It is important to note, however, that some means of returning these energy tax revenues to the economy is desirable in order to avoid the deflationary impact of extracting such a volume of income from the private economy.

There are two sets of considerations that would lead to a smaller Btu tax than that depicted in Table 22. First, imports from countries such as Canada, Venezuela and Indonesia might be regarded as sufficiently reliable that the objective of import independence might be interpreted as independence from Middle East producers. If this were the case, then a lower tax rate profile could be inferred from Table 21 as sufficient for the purpose. Second, the simulations in Table 21 are predicated on the U.S. energy production levels underlying the forecasts of the U.S. Department of the Interior (Dupree and West,1972). These allow for Alaskan North slope oil production and some new discoveries in the lower 48 states. New discoveries of oil and/or gas reserves in the U.S. would provide an alternative potential means of reducing dependence on imports. Whether such a discover, even if it were to occur in the near future, would result in a substantial contribution to domestic oil or gas output much before 1985 can be regarded as questionable. However, on the latest available information on United States domestic production and reserves of oil and gas, the figures in Table 21 for the tax rates required for energy independence are appropriate.

The relation between the rate of Btu tax and the resulting reduction in energy use is shown in Table 23. It is clear from this information that a higher tax rate leads to a greater reduction in energy use but that the relation is not one of proportionality. Increases in the tax rate have a diminishing impact on the reduction in energy use. Therefore, each additional Btu reduction in energy usage requires a larger increase in the rate of the Btu tax. Fortunately, the reduction in the effectiveness of the Btu tax is gradual, substantial reductions in energy use and in import dependence can be obtained from tax rates that are not unreasonably high in terms of revenue yield.

The impact of the various Btu taxes on energy use is given in detail in Table 24 and in Table 25. This information shows that the Btu tax has markedly different effects on the use of the different types of fuel--coal, petroleum, electricity, and gas. In each of the three years analyzed, the ranking in terms of change in energy use is substantially the same; the greatest change in use occurs in natural gas, then petroleum, then coal, and the least change in use occurs in electricity. The effect as measured by the percentage reduction in total U.S. demand for the fuel caused by the Btu tax is clearly greatest for gas usage, which in turn is substantially greater than petroleum, with coal and electricity then following without so much difference between their usage reductions.

Apart from coal, which is used almost entirely as an intermediate input, both final consumption and intermediate uses share substantial drops under the Btu tax. The impact on final demand relative to intermediate use does vary among the different fuels. In terms of the percentage reduction in use that results from the tax, consumption of petroleum products falls more in final consumption than in intermediate use, while for electricity

Table 23.

Relation Between Btu Tax Rates and Reduction in 1975 Energy Use

Tax Rate ($/m Btu)	0.041	0.0575	0.077	0.119	0.190
Reduction in U.S. Energy Use (tr Btu)	3007	3931	5188	7782	11845
Energy Reduction/Tax Rate	73341	68365	67376	65395	62342

Table 24.

Impact of Btu Taxes on U.S. Energy Use

(Energy flows in Trillion Btu)

	Final Consumption			Intermediate Use			Total U.S. Demand		
					1975				
Tax Rate ($/m Btu)	0	0.0575	0.119	0	0.0575	0.119	0	0.0575	0.119
Coal	71	69	68	13671	13130	12585	13742	13199	12663
Refined Petroleum	15542	14553	13597	18698	18097	17484	34241	32650	31080
Electricity	3106	3039	2968	4169	4016	3861	7275	7055	6830
Gas	7874	7131	6447	17118	16284	15448	24992	23415	21895
Total	26593	24792	23080	53657	51527	49388	80250	76319	72468
					1980				
Tax Rate ($/m Btu)	0	0.184	0.290	0	0.184	0.290	0	0.184	0.290
Coal	86	81	79	16603	15012	14222	16688	15094	14301
Refined Petroleum	18522	15587	14201	23040	21262	20313	41561	36848	34514
Electricity	4663	4370	4213	5563	5025	4747	10226	9395	8960
Gas	8984	7000	6138	19224	17067	15944	28208	24068	22081
Total	32254	27039	24631	64430	58366	55225	96684	85405	79856
					1985				
Tax Rate ($/m Btu)	0	0.480	0.640	0	0.480	0.640	0	0.480	0.640
Coal	109	97	93	21112	17408	16448	21221	17505	16541
Refined Petroleum	22371	15402	13785	27667	23660	22439	50038	39062	36224
Electricity	6723	5763	5484	7227	5733	5332	13950	11496	10815
Gas	9712	5874	5074	21285	17204	15967	30998	23078	21042
Total	38916	27135	24436	77291	64006	60186	116207	91140	64822

Table 25.

Impact of Btu Taxes on U.S. Energy Use

(Percentage by which energy flow after introduction of the Btu tax differs from the energy flow with no tax).

	Final Consumption			Intermediate Use			Total U.S. Demand		
				1975					
Tax Rate ($/m Btu)	0	0.0575	0.119	0	0.0575	0.119	0	0.0575	0.119
Coal	0	-2.8	-4.2	0	-4.0	-7.9	0	-4.0	-7.9
Refined Petroleum	0	-6.4	-12.5	0	-3.2	-6.5	0	-4.6	-9.2
Electricity	0	-2.2	-4.4	0	-3.7	-7.4	0	-3.0	-6.1
Gas	0	-9.4	-18.1	0	-4.9	-9.8	0	-6.3	-12.4
Total	0	-6.8	-13.2	0	-4.0	-8.0	0	-4.9	-9.7
				1980					
Tax Rate ($/m Btu)	0	0.184	0.290	0	0.184	0.290	0	0.184	0.290
Coal	0	-5.8	-8.1		-9.6	-14.3	0	-9.6	-14.3
Refined Petroleum	0	-15.8	-23.3		-7.7	-11.8	0	-11.3	-17.0
Electricity	0	-6.3	-9.7	0	-9.7	-14.7	0	-8.1	-12.4
Gas	0	-22.1	-31.7	0	-11.2	-17.1	0	-14.7	-21.7
Total	0	-13.1	-23.6	0	-9.4	-14.3	0	-11.7	-17.4
				1985					
Tax Rate ($/m Btu)	0	0.480	0.640	0	0.480	0.640	0	0.480	0.640
Coal	0	-11.0	-14.6	0	-17.5	-22.1	0	-17.5	-22.1
Refined Petroleum	0	-31.2	-38.4	0	-14.5	-18.9	0	-21.9	-27.6
Electricity	0	-14.3	-18.4	0	-20.7	-26.2	0	-17.6	-22.5
Gas	0	-39.5	-47.8	0	-19.2	-25.0	0	-25.6	-32.1
Total	0	-30.3	-37.2	0	-17.2	-22.1	0	-21.6	-27.2

intermediate use falls more and for gas final use shows the greater reduction.

The different relative impacts of the uniform Btu tax on the various fuels can be attributed to various factors. Electricity is already the most expensive source of energy. The 1971 cost per Btu for the different fuels are shown in Table 26. Electricity is four times as expensive per Btu as the next most expensive fuel, petroleum. Each dollar of tax per Btu results in a smaller relative increase in the price of electricity than in the price of other fuels; this is detailed in the price information in Table 19. Thus, electricity becomes relatively less expensive than other energy sources, leading to some substitution of electricity for these other fuels. Also, electricity is such a convenient and flexible energy source that, for many users, it has no close substitute and its use is relatively insensitive to changes in price.

Coal usage falls only slightly more than usage of electricity, but for different reasons. From Table 26 coal can be seen to be much the cheapest energy source and even after its price has risen to accomodate the Btu tax, it is still relatively cheap for those uses to which it is suited, particularly industrial and electricity generating fuel. Lack of availability of substitute fuels in similar quantities, with similar reliability of supply or as cheaply as coal, results in a smaller reduction in coal use than in the use of any other primary energy source.

Consumption of petroleum products is reduced initially by the reduction in imports and the consequent rise in price. The rise in the prices of petroleum products caused by the tax leads to significant reductions in usage, particularly in the final consumption level. Natural gas is similar but is subject to more competition from substitute fuels. Given the substantial rise in price of natural gas, added to a price already artifiically low due to price regulation, there is a substantial reduction in usage of gas, particularly in final consumption.

Table 26.

Energy Costs of Different Fuels, 1971

($1971mn/tr Btu)

	Average Cost
Coal	0.36
Petroleum Products	1.23
Electricity	5.00
Gas	0.74

The impact of the Btu taxes on prices is shown in Table 27. Taxes on energy lead to higher energy prices and these, in turn, filter through the entire economic system, raising prices in all sectors. The effect on overall prices, as measured by the average price of goods and services, for example, is not substantial. In 1985, under a Btu tax system sufficient to achieve energy independence, the overall price level is 3.1% higher than it would have been without an energy tax. Inflation would average 3.3% a year with the tax as opposed to 3.0% without it over the period to 1985.

The impact of the Btu tax on the energy sector prices varies markedly between the different fuels--electricity prices increase the least, in percentage terms, since electricity is already expensive in terms of Btu. The price of coal does not increase much more in price than electricity since supply conditions in the coal industry are such that only part of the tax is passed on to purchasers. Petroleum products increase in price by more than electricity as demand conditions permit the tax to be passed on in the form of higher prices. Natural gas prices behave similarly, but increase even more than petroleum prices. The average percentage increase in prices for a Btu tax of $1 million per trillion Btu is given in Tabel 28 although it should be noted that the relation between tax rate and price increase is not proportional--increases in prices increase with taxes but not as rapidly.

The effect of the Btu taxes on output is shown in Table 29. The reduction in energy use caused by the Btu tax does have a cost in production and consumption. This cost is not, however, very large--energy independence by 1985 leads to output in that year only 1.6% below the output that would have been possible if there had been no restriction on imports and no Btu tax. The sectoral impact of the tax is primarily on output of the energy sectors.

Table 27.

Effect of Btu Taxes on Prices

(Percentage difference of the average output price of each sector with the tax imposed from the price with no tax)

	1975			1980			1985		
Tax Rate ($/m Btu)	0	0.0575	0.119	0	0.184	0.290	0	0.480	0.640
Agriculture	0	0.3	0.6	0	0.8	1.2	0	1.7	2.3
Manufacturing	0	0.3	0.6	0	0.7	1.2	0	1.7	2.2
Transport	0	0.3	0.7	0	0.9	1.4	0	1.9	2.6
Services	0	0.1	0.2	0	0.3	0.6	0	0.6	0.8
Coal	0	4.3	8.9	0	11.0	17.4	0	23.2	31.0
Crude Petroleum	0	4.3	8.9	0	11.6	18.4	0	27.3	36.5
Refined Petroleum	0	6.3	13.2	0	17.0	27.4	0	39.1	53.8
Electricity	0	2.2	4.5	0	6.5	10.4	0	16.1	21.8
Gas	0	10.1	21.4	0	26.5	43.4	0	57.2	80.2
Consumer Prices	0	0.4	0.8	0	1.0	1.7	0	2.3	3.1

Table 28.

Average Effect on Prices and Output in 1985 of the Btu Tax

(Average Percentage increase of prices or output
with the Btu tax imposed over prices or output with
no tax, for a tax of $1/m Btu)

	Prices	Output
Agriculture	4.3	-4.4
Manufacturing	4.0	-4.2
Transport	4.9	-4.9
Services	1.6	-2.5
Coal	60.0	-45.0
Crude Petroleum	63.0	-43.0
Refined Petroleum	93.0	-60.0
Electricity	35.0	-44.0
Gas	145.0	-75.0
Total	5.7	-3.2

Table 28.

Effect of Btu Taxes on Output

(Percentage difference of the output with the Btu tax imposed from the output with no tax)

	1975			1980			1985		
Tax Rate ($/m Btu)	0	0.0575	0.119	0	0.184	0.290	0	0.480	0.640
Agriculture	0	-0.3	-0.7	0	-0.8	-1.3	0	-1.9	-2.4
Manufacturing	0	-0.3	-0.6	0	-0.8	-1.2	0	-1.7	-2.3
Transport	0	-0.3	-0.7	0	-0.9	-1.4	0	-1.8	-2.4
Services	0	-0.2	-0.4	0	-0.5	-0.7	0	-1.0	-1.4
Coal	0	-3.5	-6.9	0	-8.5	-12.7	0	-15.7	-19.8
Crude Petroleum	0	-3.3	-6.5	0	-8.2	-12.2	0	-16.1	-20.0
Refined Petroleum	0	-4.7	-9.3	0	-11.4	-17.0	0	-22.0	-27.7
Electricity	0	-3.0	-6.1	0	-8.1	-12.3	0	-17.6	-22.5
Gas	0	-6.3	-12.4	0	-14.7	-21.7	0	-25.6	-32.2
Total Output (GNP)	0	-0.3	-0.5	0	-0.6	-0.8	0	-1.3	-1.6

As has been discussed already, the impact is, among the energy sectors, least for electricity, slightly more for coal, more for petroleum and most for gas. Economizing on fuel use and substitutions between fuels in the producing sectors, along with the fact that the main burden of energy reduction falls directly onto final consumers, permit the other producing sectors to continue with only minimal impact from the tax and energy cutbacks.

Transportation is most affected by the tax, with agriculture and manufacturing affected almost as much; but output of services is reduced very little. The average effect on sectoral output of a one dollar tax per million Btu is shown in Table 28. All these output figures show that a Btu tax high enough to achieve energy independence by 1985 would not significantly reduce real economic growth; in fact, the rate of growth of real GNP would be reduced by only about 0.15 percent points per year, compared to growth with no limits on imports and no energy tax.

This discussion of energy tax in the form of a uniform tax per Btu on all energy sources can be summarized as follows:

1. A Btu tax does give effective control over total U.S. energy usage.

2. A Btu tax program would be adequate to achieve energy independence by 1985; the tax rates required for this would not be unreasonably high in terms of revenue yield.

3. A Btu tax to secure energy independence would result in higher prices, particularly of energy products, but the average increase in the rate of inflation would only be in the order of 0.3 percentage points a year.

4. A Btu tax to secure energy independence would have a cost in terms of reduction in output but real growth would continue with the reduction in the rate of growth only in the order of 0.15 percentage points a year.

5. A Btu tax to secure energy independence would have differing effects on different fuels--electricity and coal output would be reduced the least; output of petroleum products and natural gas, the most.

Footnotes

1. The seminal contribution to macro-econometric modeling of the U.S. economy is the Klein-Goldberger (1955) model. For a recent review of macro-econometric models of the United States, see Hickman (1972).

2. For the original development of input-output analysis, see Leontief (1951). A recent compendium of research on input-output analysis is Carter and Brody (1970).

3. A more detailed presentation of our approach is contained in Jorgenson, Berndt, Christensen, and Hudson (1973).

4. In the Klein-Goldberger model the determination of prices can be completely suppressed with a resulting improvement in forecasting accuracy for real magnitudes. See Suits (1962) and Goldberger (1959).

5. The energy balance framework has been employed by Dupree and West (1973) and The National Petroleum Council (1971, 1972).

6. See, for example, the discussion of the neo-classical two sector growth model by Burmeister and Dobell (1970) and the references given there. A more detailed discussion of our model is presented in Hudson and Jorgenson (1974); see also, Jorgenson, Berndt, Christensen, and Hudson (1973), Chapter 2.

7. Detailed projections are presented by Hudson and Jorgenson (1974b).

8. Our model of the household sector was originated by Christensen and Jorgenson (1968). Our model of the business sector was originated by Christensen, Jorgenson, and Lau (1973).

9. The data are presented in a series of articles by Christensen and Jorgenson (1969, 1970, 1973a, 1973b).

10. Energy imports are significant only for crude and refined petroleum products, and natural gas. For the period 1958-1972 petroleum imports were subject to a system of quotas. Natural gas imports are subject to regulation by The Federal Power Commission. For a discussion of the petroleum import quota system, see Barrows and Domencich (1970).

11. For a detailed interpretation of the price possibility frontier, see Christensen, Jorgenson and Lau (1973), esp. pp. 32-33.

12. See Samuelson (1966).

13. For further discussion of the model of producer behavior, see Section 4, below.

14. The idea of treating input-output coefficients as functions of prices can be traced to Walras (1954), esp. pp. 382-392; this approach has been extensively discussed by Samuelson (1966), pp. 513-536, and Morishima (1964), pp. 54-92. A more influential idea is to model trends in input-output coefficients without treating them as part of a model of producer behavior. This alternative approach has been employed by Leontief (1953),

Carter (1970) and Almon, et al. (1974). Comparisons of input-output coefficients for 1947, 1958 and 1961 are given by Carter (1970) and Vaccara (1972).

15. For a detailed discussion of the indirect utility function, see Chirstensen, Jorgenson, and Lau (1974).

16. This Section is based on Berndt and Jorgenson (1973).

17. See Christensen, Jorgenson, and Lau (1973), pp. 29-32.

18. See Leontief (1947).

19. See Christensen, Jorgenson, and Lau (1971).

20. A KLEM model for total U.S. manufacturing based on the translog price possibility frontier has been developed by Berndt and Wood (1974). Berndt and Christensen (1973, 1974a, 1974b) have developed models of capital-labor substitution for U.S. manufacturing based on the translog production function, which is dual to the translog.

21. Methods for imposing convexity restrictions have been developed by Lau (1974).

22. These data were compiled by Jack Faucett Associates (1973).

23. The minimum distance estimator for non-linear simultaneous equations is discussed by Malinvaud (1970), pp. 325-373.

24. See footnote 5, above.

25. The conversion factors are given in Table 26, below.

26. See National Petroleum Council (1972).

27. See: Chapman, Mount, and Tyrrell (1972); a detailed report on the econometric model underlying these projections is given by Mount, Chapman, and Tyrrell (1973).

28. See footnote 2 above for references to the projections by the National Petroleum Council; see National Economic Research Associates (1972).

29. See Federal Power Commission (1971).

30. This section is based on Hudson and Jorgenson (1974a), presented as testimony at hearings by the Senate Finance Committee, January 16, 1974.

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ECONOMIC ANALYSIS OF ALTERNATIVE ENERGY GROWTH PATTERNS, 1975 - 2000*

Edward A. Hudson

Summary

This study presents the results of simulations of U.S. economic growth over the 1975-2000 period under different energy supply and demand conditions. The economic impacts of moves from historical growth patterns to an "energy technical fix" growth path, and from this to a "zero energy growth" path are examined. The main conclusions are:

(i) Substantial economies in U.S. energy input are possible within the existing structure of the economy and without having to sacrifice continued growth of real incomes.

(ii) This energy conservation does have a non-trivial economic cost in terms of a reduction in real income levels vis-a-vis the historical growth position; in 2000 real income under technical fix growth and zero energy growth are both about 4% below the historical growth figure.

(iii) Adaptation to a less energy intensive economy will not have a cost in terms of reduced employment; in fact it will result in a slight increase in demand for labor. This, with the reduced real output, means that labor productivity is reduced and, correspondingly, real wages are slightly lower in technical fix or zero energy growth than in historical growth.

(iv) Adaptation to a less energy intensive economy will not have a cost in terms of total capital requirements; in fact, technical fix or zero energy growth should require slightly less total capital input than historical growth.

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*A Report to the Energy Policy Project, Ford Foundation.

(v) The shift to reduced energy use will result in an increase in rates of inflation from a predicted 3.8% a year under historical growth to 4.1% under zero energy growth.

The quantitative economic changes involved in the move to technical fix or zero energy growth are summarized in Table 1.

Table 1

Summary of Differences Between Growth Paths
(percentage difference in the level of
each variable between growth paths)

	Historical vs. Technical Fix		Historical vs. Zero Energy Growth		Technical Fix vs. Zero Energy Growth	
	1985	2000	1985	2000	1985	2000
Real GNP	-1.64	-3.78	-1.61	-3.54	0.03	0.25
Price of GNP	2.00	4.81	2.26	6.03	0.25	1.17
Employment	0.90	1.52	1.25	3.32	0.35	1.77
Capital input	-1.02	-1.83	-0.88	-1.17	0.15	0.67
Energy input	-16.6	-37.7	-19.3	-46.1	-3.2	-13.4

Introduction

This report examines and compares the general economic environment corresponding to the three alternative energy growth patterns being studied by the Energy Policy Project. These growth patterns are (i) historical growth where past energy supply and demand patterns are assumed to continue into the future, (ii) "technical fix" growth where energy conservation practices and known energy saving technologies are incorporated into production and consumption patterns to the extent possible within existing life styles and economic organization, and (iii) "zero energy growth" (ZEG) where, in addition to the technical fix measures, changes in life styles and economic structure are introduced in order to move towards a situation of constant per capita energy consumption. Economic growth paths under each of these three scenarios were simulated using the DRI energy model. The DRI energy model simulates production, transactions and consumption aspects of the economy to generate predictions of sectoral output levels, sectoral prices and patterns of energy use. These data can then be used to obtain a broad picture of the economic system along each of the alternative growth paths and most importantly, to assess the differential impact of the two energy conservation programs vis-a-vis the historical growth path. Information on the differential impacts of technical fix and zero energy growth is extremely important as it provides the basis for ascertaining the nature and magnitudes of the economic costs of the two conservation programs so that, as a basis for energy policy decisions, costs can be compared to the benefits resulting from reduced energy consumption.

The conclusion of this study is that the transition to technical fix growth, or even to zero energy growth, can indeed be accomplished within the current economic structure without major economic upheaval or collapse.

A final purpose of this report is to complement other, technically oriented, studies of energy consumption being conducted by the Energy Policy Project so that each approach can be used to cross-check the other. Specifically, the present economic approach, conducted at an aggregate level and incorporating known patterns of economic complementarity, substitutability and adjustment, provides a broad based measure of the impact of reduced energy use on general production whereas an engineering or process approach which examines possibilities for and consequences of energy conservation at the detailed production or consumption level will produce a detail based measure of the impact of energy reduction on production. It emerges that the economic and engineering approaches are indeed in general agreement.

The DRI Energy Model

The DRI energy model has already been presented in detail in the DRI report to the Energy Policy Project: "Energy Resources and Economic Growth," DRI, September 30, 1973. This section presents a brief outline of the model with the intention of illustrating the general derivation of the results presented below. The model is based on an interindustry model of the U.S. economy in which production and consumption are broken down in the following pattern:

(i) production is classified into nine sectors, each of which is represented by a production submodel. These nine sectors are agriculture (together with nonfuel mining and construction), manufacturing, transport, services (together with trade and communication), coal mining, crude petroleum and natural gas extraction, petroleum refining, electric utilities, and gas utilities.

(ii) the nine producing sectors purchase inputs of primary factors - imports, capital services and labor services.

(iii) the nine producing sectors must also purchase inputs from each other e.g. manufacturing makes purchases from transport and the transport sector makes purchases of manufacturing output.

(iv) the nine producing sectors then sell their net output to final users - personal consumption, investment, government and exports.

These components are then integrated within an interindustry, or input-output, model. The feature of input-output analysis is that transaction flows are brought into consistency so that each sector produces exactly that amount needed to meet final demands as well as the intermediate demands from other producing sectors. The critical feature of the DRI energy model is that the patterns of input into the producing sectors, as well as the final demand levels, are functions of, inter alia, prices. This means that the model allows for production to substitute, within the bounds of given technical parameters, relatively less expensive for relatively more expensive inputs. This feature is of central importance in energy analysis for it captures the fact that producers and consumers react to higher energy prices by economizing on energy use by substitutions between different fuels, and by substitutions between fuel and non-fuel purchases, as well as by cutting back on "nonessential" energy input without accompanying substitutions.

The actual solution of the model moves through the following steps:

(i) prices are determined endogenously in terms of production coefficients, efficiency levels, primary input prices and other information,

(ii) these prices are then used to solve for the pattern of inputs into each producing sector that is most economical in terms of these prices,

(iii) these prices are also fed into final demand submodels to obtain final demands for each type of output,

(iv) the input-output system is then solved to find the primary inputs and the interindustry transactions that are required to satisfy these final demands. Thus, the model simulates, on the base of exogenous parameters characterizing the general economic environment, the entire flow of transactions in the economy - transactions from factors to producers, producers to producers and producers to consumers. Specifically, the model generates transactions flows and totals in current dollars and real terms (constant dollars) together with the corresponding sectoral price levels and energy usages.

Methodology

The simulations of the alternative energy scenarios were made in two steps. First, the DRI energy model was calibrated so as to produce the Energy Policy Project historical growth path of economic development. This involved selecting and inserting into the model initial assumptions covering productivity advance, fuel imports, income growth, primary input prices, energy supply conditions and so on in such a way that the predicted energy demand growth path exhibited the same general characteristics and trends as observed in historical energy growth patterns. Once the model was calibrated in this way the exogenous assumptions were fixed and only those parameters corresponding to a move from historical energy use patterns to a technical fix situation and then from technical fix to a zero energy growth situation were varied. In other words, the general specification of the model was held unchanged in the three different energy scenarios, only energy specific parameters were varied to secure the move between the three alternative growth paths.

The simulations focused on three years - 1975, which was used as the common starting point for all three alternative growth paths, 1985, when the three growth paths had clearly diverged, and 2000, by which time the full effects of each energy conservation program had been felt and the differential impacts of the energy conservation programs were most clearly visible. Thus three economic growth paths, starting from the same initial position in 1975, are examined at two points in time - 1985 and 2000. The differences between the growth paths can still be examined in detail; limiting the comparison to two years has no cost, but saves the complexity involved in simulating every year from 1975 to 2000. The solution presupposes that the economy has had time to make the adjustment from its initial to its equilibrium configuration. The use of 1985 and 2000 as comparison years is entirely consistent with this assumption since the time lags to these years are more than sufficient to cover the transition period needed for the economy to adapt to policies and conditions implemented in the near future.

The predictions are based upon an economic model which simulates aggregate production, expenditure and consumption relationships. Since the model is a simplified and idealized representation of actual processes, its forecasts cannot be considered as pin-point accurate predictions of future economic events. Actual future developments will vary from those predicted in this study because the assumptions made about future exogenous developments may not be completely accurate and also because the model does not replicate economic processes with perfect accuracy. However, the focus of this report is on the differences in economic performance under different energy conditions rather than on future levels of economic indicators. The model does give meaningful estimates of these differences. First, because differencing itself eliminates any systematic bias introduced into the forecasts through incorrect assumptions and through biases in the model itself; second, because extensive testing of the model suggests that it does produce reasonable estimates of the changes in aggregate economic behavior produced by changes in exogenous parameters.

Historical Growth

The pattern of economic growth and energy consumption corresponding to the historical growth scenarios is summarized in Table 2. This growth pattern is, by design, essentially a continuation of recent trends so that, even in 2000, the forecast composition of the economy is similar to that of the 1975 starting point.

Production increases at rates similar to, although slightly below, recent growth rates. The decline in growth rates is expected to become significant only in the 1980's in response to the low fertility rates currently being experienced. The assumption is made that the fertility rates experienced over the 1970-73 period, rates which imply an eventually constant population size, will continue so that when today's babies begin to enter the labor force in the late 1980's, the rate of labor force expansion slows, leading to a general reduction in the rate of increase of real GNP. Per capita income and output is not reduced, but a smaller labor force means a smaller total output.

The composition of production does change somewhat over the forecast period - in terms of gross output, i.e., total sales of each sector, transport expands the most rapidly followed by the energy industries, then manufacturing, then services. These trends in composition reflect developments that can be discerned today:

Table 2

Historical Growth Path

	1975	1985	2000	Growth Rates	
				1975-85	1985-2000
				(% per annum)	
Output (gross) ($1971 Billion)					
agriculture	306.8	387.9	532.2	2.4	2.1
manufacturing	848.6	1228.4	1966.1	3.8	3.2
transport	94.4	140.2	244.8	4.0	3.8
services	976.6	1364.7	2109.5	3.4	2.9
energy	97.8	144.3	249.6	4.0	3.7
Demand					
consumption	838.3	1211.8	1990.9	3.8	3.4
investment	309.7	430.5	670.4	3.3	3.0
government	275.0	388.4	604.9	3.5	3.0
net exports	19.2	33.2	78.8	5.6	5.9
GNP	1442.2	2064.0	3345.0	3.6	3.3
Output (value added)					
agriculture	135.8	186.6	290.1	3.2	3.0
manufacturing	345.1	459.2	662.5	2.9	2.5
transport	52.3	64.3	82.7	2.1	1.7
services	703.3	1011.2	1669.6	3.7	3.4
energy	63.1	101.3	190.4	4.9	4.3
services of durables	142.6	226.6	446.8	4.7	4.6
Employment (Billion manhours)					
agriculture	16.478	19.696	26.006	1.80	1.87
manufacturing	41.689	48.049	59.807	1.43	1.47
transport	6.927	7.524	8.683	0.83	0.96
services and government	105.452	129.834	168.061	2.10	1.74
total	173.115	205.103	262.557	1.71	1.66
Energy (Quadrillion Btu)					
coal	13.15	18.54	34.40	3.49	4.21
petroleum	34.87	39.48	58.91	0.36	2.70
electricity	6.81	13.16	27.37	6.81	5.00
gas	24.47	34.51	42.23	3.50	1.35
nuclear, other	5.55	22.50	51.25	15.02	5.64
Total energy input	78.03	115.03	184.71	3.96	3.21
Energy consumption (Quadrillion Btu)					
pers. consumption	23.165	31.606	48.359	3.2	2.9
services and government	10.936	15.480	26.743	3.5	3.7
electricity generation	21.080	40.739	84.716	6.8	5.0
industry	26.900	36.900	49.476	3.2	2.0
transport	2.672	3.469	4.867	2.6	2.3
total input	78.032	115.031	184.706	4.0	3.2

Table 2 continued

	Growth Rates	
	1975-1985	1985-2000
Prices	(%per annum)	
agriculture	4.70	5.09
manufacturing	3.04	3.68
transport	2.03	2.56
services	3.88	4.23
coal	1.78	5.72
crude petroleum	4.76	4.44
refined petroleum	5.74	4.54
electricity	-0.90	2.53
gas	5.96	4.94
consumption	3.63	3.98
investment	3.58	4.08
government	3.79	4.16
GNP	3.61	3.98

(i) increased demand for transport for business and vacation travel, and to service increasingly dispersed economic activity, together with some increase in the relative importance of public transport, result in a continued rapid increase in transport activity;

(ii) energy output also grows rapidly in large part because of the rapid growth of electricity usage which, since electricity is a secondary energy form suffering large energy conversion losses, places great demands on the primary energy sources;

(iii) manufacturing output grows in line with total production driven both by demand for manufactured goods as an input into the other producing sectors as well as by continuing growth in final use demands for manufacturing output;

(iv) services grow less rapidly than manufacturing in terms of total output for, although final demand for services in current dollars is rising more rapidly, the faster rate of price increase for services converts this to a slower rate of increase in real output. The historical forecast implies a continuation of the relative increase in the importance of service activities, but services prices increase more rapidly than those of manufacturing leading to real service output growing less rapidly than real manufacturing output;

(v) agriculture and construction real output grows at the slowest rate, primarily because demand for these types of output is linked to population more than income so that increasing consumption demand flows more to the other producing sectors.

The value added in each production sector moves a little differently from the growth pattern of real output. Services of consumer durables show the fastest increase, i.e., the imputed flow of services to consumers from owner-occupied housing, automobiles and other home and personal appliances increases more than market transacted output. The greatest rate of increase in value added in marketed output occurs in energy production - the rapidly growing demand for energy sources along with the increasingly difficult supply conditions in fuel production, result in inputs being drawn into these sectors relative to other production. Services show the next most rapid increase and are predicted to continue to increase relative to real GNP. This increase is due to the continuing rapid growth of final demand for services, along with the very low rate of productivity advance expected in service activities, drawing capital and labor services into service occupations faster than the general rate of increase in the supply of these inputs. This process is reflected also in the increasing share of services in total employment. Agriculture and construction value added increases less rapidly than GNP, mainly because total demand for output from these activities is not growing as rapidly as GNP. Manufacturing and transport value added increases least rapidly of all sectors. The reason for this is the continued high rate of productivity advance expected in these activities since this allows their output to increase without a correspondingly rapid increase in primary inputs.

The employment pattern changes in a similar way to value added with services, agriculture and construction increasing and manufacturing and transport declining in relative importance. Services and government increase their share of total employment from 60% to 64% over the forecast period. Employment as a whole increases at around 1.7% a year although this rate of increase declines over time due to the effect of low fertility rates in slowing labor force growth.

Prices are projected to increase at around 3.75% a year which, although not as rapid as the inflation currently being experienced, is still substantially faster than average inflation rates of the last ten or fifteen years. On the demand side consumption, investment and government purchases price indices all rise at about the same pace. On the production side however, there is more substantial variation in rates of price increase. Fuel prices, apart from electricity, rise the fastest of any prices as it becomes increasingly difficult to produce the fuel to meet the rapidly growing demand. Electricity prices show much less increase. The reason for this lies in the productivity assumptions upon which the historical growth forecasts are based. The past rapid growth in electricity use has been, in large part, due to the past steadiness, and even decline, in electricity prices which, in turn, have been made possible by a very rapid rate of productivity increase in the electricity generation sector. This productivity advance has moderated in the past four years due, apparently, to short run influences but, in line with the historical conditions objective of the historical growth forecast, this slowdown is assumed to be temporary with productivity advance in electricity generation returning to typical past rates. This efficiency permits fuel, capital and labor price increases to the electricity generation sector to be absorbed without comparable increases in electricity sales prices.

Nonfuel prices also show differences in their growth rates. Productivity advance in manufacturing and transport allows these sectors to absorb some input price increases with the result that their output prices increase a little less rapidly than the general rate of inflation. Service, agricultural and construction activity, however, does not exhibit such rapid productivity growth and this, together with their relative intensity of use of an input, labor, whose price is rapidly increasing, causes their prices to rise more rapidly than general inflation.

Energy use continues broadly along past trends. The dominant feature in energy is the rapid increase in the consumption of electicity. This increase is partially due to the productivity and price behavior of electricity generation already discussed . The growth in electricity production leads to rapid growth in the use of primary fuels used in the generation of electricity, with this growth being evidenced primarily in nuclear generation but also in the demand for coal. Petroleum and gas consumption, on the other hand, increase more slowly for here the price increases resulting from demand facing a restricted supply lead to some moderation in the demand for these fuels. Total U.S. energy input increases by around 3.5% a year which is close to past average rates of increase.

This historical growth projection corresponds, approximately speaking, to assuming a continuation of the conditions, especially those relating to energy supply, pertaining in the 1960's. Developments of the recent past such as limitations on fuel imports, restrictions on construction of nuclear electricity plants, slower productivity growth in electricty generation, restrictions on oil and gas exploration and production, major increases in fuel prices and so on are not incorporated in the historical growth projections. In other words, these projections assume no significant price or regulatory pressure to alter energy demand and no serious problems in obtaining the fuel resources to satisfy these demands.

Recent events have shown the set of assumptions underlying the historical growth forecast to be unrealistic. Thus, although this forecast is extremely useful as an analytical reference point, we need to supplement it by alternative forecasts which incorporate the recent energy developments. Therefore, we now proceed to examine the technical fix and zero energy growth alternative growth paths, both of which incorporate less favorable conditions concerning the availability of energy or which, alternatively, could be viewed as projections of economic growth under policies designed to restrict energy demand.

Technical Fix Growth

The growth path of the economy under technical fix conditions is summarized in Table 3. Also, this table shows the difference between the historical and the technical fix growth paths. The summary information is that, in 2000, a reduction of 37% in total energy input can be accomodated with only a 3.8% decrease in real GNP, a small increase in the rate of inflation and without any increase in unemployment. That is, the economy can adjust to a substantial decline in energy use without major dislocation. The differences between the historical growth and the technical fix growth paths are now considered in more detail.

The motivating forces introduced into the energy model to secure the move from the historical growth path to the technical fix growth path were increases in petroleum products prices and in electricity prices. These price increases, when their impact on other prices, on input patterns and on demand levels has been solved through, lead to a new economic configuration requiring a reduced energy input. The critical output from this analysis is the economic changes that are produced by these price increases; the underlying cause of the price increases is not directly relevant. In fact, the initial price increases in the model were secured by assuming unfavorable domestic petroleum supply conditions and restrictions on imports of petroleum, which served to produce a dramatic increase in petroleum product prices, and by assuming a continuation of recent slow productivity advance in electricity generation, which served to increase electricity prices. (The corresponding historical growth assumptions were that domestic oil production and/or imports could expand to accomodate petroleum demand growing at historical rates, and that electricity generation productivity advance

Table 3

Technical Fix Growth

	1975	1985	2000	Growth Rates 1975-85	 1985-20	difference from historical growth level (%) 1985	 2000
Output (gross) ($1917)				(% per annum)			
agriculture	306.8	381.3	512.3	2.2	2.0	-1.70	-3.74
manufacturing	848.6	1214.3	1906.1	3.6	3.1	-1.15	-3.05
transport	94.4	138.3	236.6	3.9	3.6	-1.36	-3.35
services	976.6	1347.8	2045.5	3.3	2.8	-1.24	-3.03
energy	97.8	115.4	144.0	1.7	1.5	-20.03	-24.31
Demand							
consumption	838.3	1188.2	1904.5	3.5	3.2	-1.96	-4.35
investment	309.7	425.9	652.2	3.2	2.9	-1.07	-2.71
government	275.0	383.1	585.5	3.4	2.9	-1.36	-3.21
net exports	19.2	33.0	76.7	5.6	5.8	-0.60	-2.66
GNP	1442.2	2030.2	3218.5	3.5	3.1	-1.64	-3.78
Output (value added)							-1.72
agriculture	135.8	185.5	285.1	3.2	2.9	-0.59	-1.72
manufacturing	345.1	456.3	650.8	2.8	2.4	-0.63	-1.77
transport	52.3	63.5	80.8	2.0	1.6	-1.24	-2.30
services	703.3	1010.6	1658.8	3.7	3.4	-0.06	-0.65
energy	63.1	76.5	96.2	1.9	1.5	-24.5	-49.5
services of durables	142.6	226.6	446.8	4.7	4.6	0.0	0.0
Employment (Billion manhours)							
agriculture	16.478	19.696	25.962	1.80	1.86	0.00	-0.17
manufacturing	41.689	47.914	59.454	1.40	1.44	-0.28	-0.59
transport	6.927	7.452	8.488	0.74	0.86	-0.96	-2.25
services and government	105.452	130.262	168.532	2.13	1.74	0.33	0.28
total	173.115	206.949	266.548	1.80	1.70	0.90	1.52
Energy (Quadrillion Btu)							
coal	13.15	17.37	25.13	2.82	2.49	-6.31	-26.95
petroleum	34.87	31.58	37.30	-0.99	1.12	-20.01	-36.68
electricity	6.81	9.43	13.51	3.31	2.43	-28.34	-50.64
gas	24.47	32.36	32.04	2.83	-0.07	-6.23	-24.13
nuclear, other	5.55	14.62	22.57	10.17	2.94	-35.02	-55.96
Total energy input	78.03	95.92	115.00	2.09	1.22	-16.61	-37.74
Energy consumption (Quadrillion Btu)							
pers. consumption	23.165	26.085	27.264	1.2	0.3	-17.5	-43.6
services and government	10.936	13.548	17.836	2.2	1.9	-12.5	-33.3
elec. generation	21.080	29.198	41.506	3.3	2.4	-28.3	-51.0
industry	26.990	33.295	30.787	2.1	1.2	-9.8	-19.6
transport	2.672	3.232	4.161	1.9	1.7	-6.8	-14.5
total input	78.032	95.924	115.005	2.1	1.2	-16.6	-37.7

Table 3 continued

	Growth Rates		difference from historical growth level (%)	
	1975-85	1985-2000		
Prices	(% per annum)		1985	2000
agriculture	4.85	5.20	1.48	3.20
manufacture	3.13	3.81	0.89	2.67
transport	2.13	2.63	1.00	2.05
services	3.98	4.31	1.00	2.31
coal	2.63	7.52	8.59	40.30
crude petroleum	3.85	4.60	-8.37	-6.15
refined petroleum	8.38	6.11	27.98	59.98
electricity	4.33	5.66	67.27	162.56
gas	6.12	6.41	1.50	25.05
consumption	3.88	4.22	2.46	5.95
investment	3.69	4.19	1.07	2.80
government	3.94	4.30	1.39	3.31
GNP	3.82	4.17	2.00	4.81

returned to its rapid, historical trends after the slowdown of the past four years). Alternatively, the price increases might be viewed as being produced by taxes on petroleum and electricity sales with the revenue being returned to the private sector by decreases in income taxes, or the results might just be viewed as showing the effect of petroleum and electricity prices on the rest of the economy, without specifying the cause of the price rises. The main results concern the economic differences between the historical and the technical fix growth paths and it is these differences which we now examine.

The technical fix growth path involves an increase in energy input at a little less than half the rate associated with historical growth, specifically at 1.6% a year instead of at 3.5%. The comparative reduction in energy use is 17% in 1985 and 38% in 2000. This reduction is concentrated in electricity and petroleum use. In 1985 electricity and petroleum consumption are each reduced by over 20% while the reduced electricity output leads to a reduced level of coal use and to a substantial reduction in nuclear input. But, higher petroleum and electricity prices lead to an increase, due to inter-fuel competition and substitution, in the price of gas. This produces a decline in use of all fuels, although the gas and coal use reduction is of a smaller order of magnitude than the reduction in petroleum and electricity use. Similarly, in 2000, electricity consumption (and nuclear input) are reduced by 50%, with petroleum use down by 37% and coal and gas use down by 25%.

Higher petroleum and electricty prices lead to a general upward pressure on prices due both to the consequent increase in production costs and to the redirection of demand and input patterns which places more demand pressure on other production. Thus, in 2000 for example, the electricity price more than doubles and the petroleum products price goes up by 60%

which leads to smaller, but still substantial, increases in coal and gas prices, as well as to significant increases in prices of nonfuel products, increases the range 2 to 3%.

On the demand side, the higher energy prices have a substantial and immediate impact on the price index of consumption goods and services and this increase is further boosted by the rise in prices of nonfuel goods and services. Thus, the rise in consumption prices is double the rise in prices of investment and government purchases. However, the overall impact on prices is not catastrophic - the GNP price deflator is increased by about 4% which corresponds to a 0.2 percentage point higher rate of inflation under technical fix than under historical growth i.e., inflation increases from 3.8% to 4.0%.

Output and real incomes are reduced slightly by the reduction in energy use but the reduction, although significant, is not catastrophic - real GNP under technical fix is 1.6% lower in 1985 and 3.8% lower in 2000 than the corresponding historical growth path levels. Energy output suffers the greatest reduction, a fall of 42% in constant dollar terms in 2000 for example. But other output is not drastically affected. Services output is reduced the least with agriculture output reduced the most, but the reductions, even in 2000, are only of the order of 3%. In terms of value added, service output is hardly affected while other output is reduced by about 2% in 2000. On the final use side, personal consumption suffers the greatest reduction but even in 2000 real consumption is only 4.4% below the historical growth level. Total output, as measured by real GNP, is reduced by 3.8% in 2000 which corresponds to a reduction in real growth rates of 0.15 percentage points, from 3.42% a year to 3.26% .

The relatively small impact of such a large reduction in energy use on real output is a striking and important result. Its economic explanation lies in the following considerations.

(i) Final demand energy use is curtailed as a result of higher energy prices. This may take the form of turning down thermostats, switching to smaller cars, installing home insulation and so on (these avenues for energy conservation mean that, after a transition period, lower energy input is consistent with the original level of effective energy based personal and household services). This reduction has very little impact on the rest of the economy for the demand reduction corresponds to only a part of the output of what is, in economic terms, a relatively small sector of the economy. Even in the 2000 historical growth projection the energy producing sectors represent only 4.2% of the entire economy in terms of gross output and 5.7% in terms of value added. Since, in turn, personal consumption use of energy absorbs only about one third of total fuel output, it can be seen that the direct impact of a reduction of personal energy consumption on the total output of the economy is not very large.

(ii) Use of energy in producing sectors can be reduced somewhat without reducing output merely by reducing waste and by adopting more energy efficient techniques. Further, there exist significant scope for substitutions between inputs into production and the emergence of higher fuel prices stimulates use of nonenergy intensive inputs. One area where this is important concerns capital input - capital and energy are complementary so higher energy prices leadsto reduced use of capital services and to the substitution of other inputs, particularly labor, for these services. The results of this substitution process are illustrated by the behavior of capital and labor inputs under technical fix growth - in 2000 for example, capital input is reduced by 1.8% from the historical growth level whereas labor input increases by 1.5%. Also, substitutions between capital and materials, between capital and services and between other inputs are possible. The net result is that producing sectors can achieve substantial economies in energy use at the expense of comparatively small reductions in output.

(iii) Any saving in the use of electricity by final consumers or by producers, even if offset by increased use of other energy services, leads, due to the conversion losses in electricity generation, to approximately three times the reduction in primary energy input. Further, to the extent that the input of uranium into electricity generation is reduced, the energy saving is even greater since the enrichment of uranium by present technologies is a heavy user of energy. Thus, increases in electricity prices, and the consequent reduction in electricity use, are a powerful instrument in reducing total energy input.

The relative magnitudes of each of these forms of energy saving are shown in Table 3. In 2000, for example, the total reduction in energy input between historical growth and technical fix is 38% (69.7 Q Btu). Energy use in electricity generation is reduced by the largest proportion, 51% (43.2 Q Btu), while personal consumption use is reduced by 44% (21.1 Q Btu), service and government use by 33% (8.9 Q Btu), industrial use by 20% (9.7 Q Btu) and transport (which excludes private automobiles) use by 15% (0.7 Q Btu). This indicates that significant economies in energy use are possible in all forms of energy consumption with personal consumption, service and government economies particularly significant. The greatest Btu savings are achieved through a reduction in the inputs absorbed in electricity generation. Electricity use is reduced due to economizing in fuel use in general as well as by the partial substitution of other fuels for electricity. The net result is that electricity conservation releases 62% of the total energy savings achieved in the move to technical fix growth.

The share of energy in total real personal consumption expenditure is shown in Table 4. In historical growth conditions, energy purchases constitute an increasingly important component of consumption purchases, increasing from 5.54% in 1975 to 6.99% in 2000. The economies in personal

Table 4

Energy Use in Consumption, Manufacturing and Services

(a) Real expenditure on energy in proportion to total real expenditure (%)

	1961	1971	1975	1985	2000
Personal Consumption					
Historical growth	4.74	5.53	5.54	5.96	6.99
Technical fix			5.54	4.59	3.75
ZEG			5.54	4.43	3.23
Manufacturing					
Historical growth	1.88	2.14	2.07	2.16	2.08
Technical fix			2.07	2.08	1.68
ZEG			2.07	2.05	1.54
Services					
Historical growth	1.30	1.76	1.85	2.14	2.58
Technical fix			1.85	1.61	1.40
ZEG			1.85	1.55	1.21

(b) Composition of Energy Input in 2000

	Personal Consumption		Manufacturing		Services	
	Hist	T.F.	Hist	T.F.	Hist	T.F.
Coal	-	-	11.8	13.2	-	-
Petroleum	16.9	21.0	23.4	27.8	41.1	39.9
Electricity	73.6	62.5	42.0	40.8	48.4	48.8
Gas	9.4	16.4	22.8	18.2	10.4	11.3
Total energy use	100.0	100.0	100.0	100.0	100.0	100.0

(Note: Hist = Historical growth path energy use pattern.
T.F. = Technical fix growth path energy use pattern.)

energy use achieved under technical fix conditions are, however, sufficiently large to reverse this upward trend so that energy purchases in 2000 represent only 3.75% of real consumption expenditure. This is a significant reduction in the energyshare but nonetheless, energy remains an important component in consumption spending and per capita personal consumption of energy is still higher than in 1975. The composition of personal energy use is also changed in response to the relative price changes. Electricity is clearly the major energy source in both historical growth and technical fix conditions but the increase in the relative price of electricity under technical fix results in the partial substitution of both petroleum products and gas for electricity use.

Manufacturing and services also redirect their input patterns to economize on energy in response to the increase in energy prices under technical fix growth. These input patterns are shown in Table 4. Energy input into manufacturing remains stable in historical growth but, under technical fix, the input proportion is reduced, in 2000, from 2.08% to 1.68%. The overall reduction in energy use is accompanied by a redirection of energy purchases towards the relatively inexpensive fuels, particularly petroleum. In services, the trend to increasing relative importance of energy input under historical growth is reversed under technical fix so that, in 2000, energy forms 1.40% of total real inputs compared to 2.58%.

The composition of energy input in technical fix is little different from that in historical growth; energy conservation in services takes the form of general reduction in fuel use rather than substitutions between fuels. Technical considerations in services use of energy, and to a lesser extent in manufacturing, constrain the possibilities for substitution between energy forms, but those substitution possibilities that do exist, together with economy in energy input in general, permit significant reduction in service and manufacturing energy use.

The substitution between inputs and adjustment in input patterns that result from higher energy prices is shown for the manufacturing and service sectors in the following table. The forces at work are initially illustrated by the input patterns along the historical growth path for the increasing relative use of capital and decreasing use of labor along this path and are the result of the increasing relative price of labor which induces producers to substitute, within technical limits, capital for labor. Also, the relatively inexpensive energy available in historical growth leads to the continuing increase in the share of energy input. The move, from historical growth to technical fix or zero energy growth paths with its causal and induced price changes leads to a further set of adjustments being superimposed on these. The price increases primarily relate to energy but these cause, in turn, a smaller change in the structure of other prices. The induced changes in input proportions in manufacturing and services can be followed from the input proportions given in the following table. The reduction in energy input has already been outlined. But, all inputs are affected by the change in prices. In manufacturing capital-energy complementarity leads to capital input being reduced although not to the same extent as energy. The small degree of complementarity between energy and inputs of materials leads to the material input proportion being reduced. The reduction in capital, energy and materials input into manufacturing is offset by increased use of the nonenergy intensive and now relatively less expensive, input--labor serivces. Thus, in 2000, for example, labor input which is already 26% of total input under historical growth increases to 27% of input under zero energy growth. Similar forces are at work in the service sector although with slightly different results. In services capital and energy are substitutes rather than complements so increased energy prices lead to a slight increase in capital input (for example, capital might be absorbed in energy saving uses such as increased insulation, installation of more efficient heating and air

Table 5

Composition of Inputs into Manufacturing and Services

(Percentage that specified input represents in total input,
based on constant dollar purchases)

	1961	1971	1975	1985	2000
(a) Manufacturing					
Capital Input					
Historical	10.2	10.6	11.6	12.4	13.6
Tech Fix			11.6	12.4	13.5
ZEG			11.6	12.4	13.4
Labor Input					
Historical	33.4	28.2	30.0	28.1	26.0
Tech Fix			30.0	28.3	26.6
ZEG			30.0	28.4	26.9
Energy Input					
Historical	1.9	2.1	2.1	2.2	2.1
Tech Fix			2.1	2.1	1.7
ZEG			2.1	2.1	1.5
Materials Input					
Historical	54.5	59.1	56.3	57.3	58.3
Tech Fix			56.3	57.2	58.2
ZEG			56.3	57.1	58.2
(b) Services					
Capital Input					
Historical	26.5	29.6	32.7	35.6	41.4
Tech Fix			32.7	35.9	42.1
ZEG			32.7	35.9	42.3
Labor Input					
Historical	47.3	42.6	39.0	35.9	30.4
Tech Fix			39.0	36.5	31.4
ZEG			39.0	36.6	31.6
Energy Input					
Historical	1.3	1.8	1.8	2.1	2.6
Tech Fix			1.8	1.6	1.4
ZEG			1.8	1.6	1.2
Materials Input					
Historical	24.9	26.0	26.5	26.4	25.6
Tech Fix			26.5	26.0	25.1
ZEG			26.5	25.9	24.9

Note: Historical is historical growth path, Tech Fix is technical fix growth path, ZEG is zero-energy growth path. Materials are all nonfuel inputs that are purchased from other intermediate sectors and from imports.

conditioning equipment, and so on). Some complementarity exists between materials and energy so the rise in energy prices leads to a reduction in the proportion of materials inputs. Use of labor, the nonenergy intensive input, increases to replace the reduction in energy and materials inputs and to permit service production to absorb these reductions without a comparable reduction in output.

The changes in input proportions in manufacturing and services involved in the shift from historical growth to zero energy growth conditions are significant. But, these shifts are well within the range of recent experience. Thus, the largest changes in input proportions involve energy input but even these changes correspond only to reversing the historical growth trend to increasing energy inputs so that energy input proportions in 2000 are in the region of the actual 1961 proportions.

Zero Energy Growth

The economic and energy information describing zero energy growth is presented in Table 6. The move from technical fix growth to ZEG was simulated by imposing an energy sales tax (a uniform tax rate applied to each dollar of sales from the energy sector) with the tax revenue then being spent by the government on health, education and transport services (the revenue was allocated 75% to purchases of labor and services, 20% to purchases of manufactures and 5% to purchases from the transport sector). This is a dual mechanism - energy use is directly discouraged by taxes, and demand is further redirected by a change in spending patterns towards nonenergy intensive production - which is superimposed on an economy which already has adapted to the energy efficient technical fix position.

The move from technical fix to ZEG involves a reduction in energy input of 3% in 1985, and of 13% in 2000. The uniform energy tax discourages all energy use with the result that consumption of each energy source is reduced by comparable proportions - in 2000, ZEG consumption of nuclear is reduced by 11% from the technical fix position, consumption of coal is down 12%, of petroleum and electricity 13%, and of gas 16%. When compared to the historical growth energy consumption pattern, the ZEG energy consumption in 2000 is reduced by 46% with electricity and nuclear down by around 60%, and other fuels down by around 40%. The reduction in energy consumption varies between uses. The move from technical fix to ZEG in 2000 involves a 13% (15.4 Q Btu) reduction in total energy input with final demand use reduced by 15% (4.2 Q Btu), electricity generation use down by 13% (5.5 Q Btu) and industrial use, including use of electricity, down by 12% (7.3 Q Btu).

Table 6

Zero Energy Growth

						Difference (%) from level			
				Growth Rates		Historical Growth		Technical Fix	
	1975	1985	2000	1975-85 (% per	1985-2000 annum)	1985	2000	1985	2000
Output (gross) ($1971 billion)									
agriculture	306.8	380.5	507.8	2.2	1.9	-1.91	-4.58	-0.21	-0.88
manufacturing	848.6	1213.2	1898.2	3.6	3.0	-1.24	-3.45	-0.09	-0.41
transport	94.4	138.4	237.9	3.9	3.7	-1.28	-2.82	0.07	0.55
services	976.6	1350.1	2066.8	3.3	2.9	-1.07	-2.02	0.17	1.04
energy	97.8	111.7	124.9	1.3	0.7	-22.6	-49.9	-3.21	-13.3
Demand									
consumption	838.3	1185.3	1385.4	3.5	3.1	-2.19	-5.30	-0.24	-0.99
investment	309.7	424.9	643.8	3.2	2.8	-1.30	-3.97	-0.23	-1.29
government	275.0	387.8	623.3	3.5	3.2	-0.15	3.04	1.23	6.46
net exports	19.2	32.8	74.3	5.5	5.6	-1.20	-5.71	-0.61	-3.13
GNP	1442.2	2030.8	3226.7	3.5	3.1	-1.61	-3.54	0.03	0.25
Output (value added)									
agriculture	135.8	185.4	284.7	3.2	2.9	-0.64	-1.86	-0.05	-0.14
manufacturing	354.1	456.5	652.8	2.8	2.4	-0.59	-1.46	0.04	0.31
transport	52.3	63.5	80.4	2.0	1.6	-1.24	-2.78	0.00	-0.50
services	703.3	1013.2	1682.7	3.7	3.4	0.20	0.78	0.26	1.44
energy	63.1	74.7	79.3	1.7	0.4	-26.3	-58.4	-2.35	-17.6
services of durables	142.6	226.6	446.8	4.7	4.6	0.0	0.0	0.0	0.0
Employment (billion manhours)									
agriculture	16.478	19.706	26.063	1.81	1.89	0.05	0.22	0.05	0.39
manufacturing	41.689	47.982	60.028	1.42	1.50	-0.14	0.37	0.14	0.97
transport	6.927	7.452	8.562	0.74	0.93	-0.96	-1.39	0.00	0.87
services and government	105.452	130.652	179.691	2.17	2.15	0.63	6.92	0.30	6.62
total	173.115	207.667	271.274	1.84	1.80	1.25	3.32	0.35	1.77
Energy (quadrillion Btu)									
coal	13.15	16.90	22.01	2.54	1.78	-8.45	-36.0	-2.71	-12.4
petroleum	34.87	30.64	32.59	-1.28	0.41	-22.4	-44.7	-2.98	-12.6
electricity	6.81	9.15	11.73	3.00	1.67	-30.5	-57.1	-2.97	-13.2
gas	24.47	31.07	27.04	2.42	-0.92	-9.97	-36.0	-3.99	-15.6
nuclear, other	5.55	14.25	20.00	9.89	2.29	-36.7	-61.0	-2.53	-11.4
Total energy input	78.03	92.87	99.60	1.76	0.47	-19.3	-46.1	-3.18	-13.4
Energy consumption (quadrillion Btu)									
pers. consumption	23.165	25.170	22.340	0.8	-0.8	-20.4	-53.8	-3.5	-18.1
services and government	10.936	13.104	16.441	1.8	1.5	-15.3	-38.5	-3.3	-7.8
electricity generation	21.080	28.319	36.298	3.0	1.7	-30.5	-57.2	-3.0	-12.5
industry	26.990	32.245	34.448	1.8	0.4	-12.6	-30.4	-3.2	-13.4
transport	2.672	3.177	3.844	1.8	1,3	-8.4	-21.0	-1.7	-7.6
total input	78.032	92.865	99.600	1.8	0.5	-19.3	-46.1	-3.2	-13.4

Table 6 continued

Zero Energy Growth

			Differences (%) from level in			
	1975-85	1985-2000	Historical Growth		Technical Fix	
	(% per annum)		1985	2000	1985	2000
Prices						
agriculture	4.85	5.27	1.69	4.36	0.22	1.13
manufacturing	3.16	3.89	1.13	4.10	0.23	1.39
transport	2.15	2.68	1.21	3.10	0.21	1.03
services	3.99	4.34	1.09	2.76	0.09	0.44
coal	3.06	8.56	13.22	68.50	4.26	20.33
crude pet.	3.86	4.62	-8.31	-5.87	0.06	0.30
refined pet.	8.74	6.92	32.25	85.28	3.33	15.81
electricity	4.67	6.54	72.71	207.0	3.25	16.93
gas	6.57	7.39	5.95	49.68	4.39	19.70
consumption	3.91	4.29	2.77	7.33	0.30	1.31
investment	3.72	4.27	1.30	4.13	0.23	1.30
government	3.95	4.32	1.51	3.75	0.12	0.43
GNP	3.85	4.24	2.26	6.03	0.25	1.17

The tax rate required to produce the move between technical fix and ZEG is 3.3% in 1985 and 15% in 2000. The 1985 shift is comparatively small and the tax revenue is similarly small but the 2000 shift is more substantial and the revenue raised by the energy sales tax is $131 bn ($50 bn in today's prices). This substantial revenue affords the opportunity to divert a significant amount of final demand from energy intensive to nonenergy intensive types of expenditure. (In fact revenues of this size are of the order of magnitude required to sustain currently mooted national health insurance programs). The energy tax does result in substantial increases in energy prices - fuel prices in 2000 under ZEG are about 18% higher than under technical fix. Nonfuel product prices also increase, but by much smaller proportions, generally of the order of 1%. In total, therefore, ZEG involves only small increases in prices above those forecast for technical fix growth - the increase in the rate of inflation (of the GNP price deflator) is only 0.05 percentage points, from 4.03% a year to 4.08%.

Real incomes and real output are not reduced by the move from technical fix to ZEG, despite the reduction in energy consumption. The reason for this lies in the redirection of final demand caused by governmental purchases in services financed by the energy tax revenues. Reduced energy use without an exogenous change in spending patterns would lead to a reduction in real incomes and real output, as in the move from historical growth to technical fix growth, but the increase in demand for services caused by increasing government purchases creates sufficient new demand to offset the reduction in real output and, as the new demand is relatively energy nonintensive, the restoration of output and incomes can be sustained at the new lower level of energy consumption. The net effect is that, in 2000 for example, real output rises by 0.25% in ZEG compared to the technical fix position, despite the 13% reduction in energy use. The gain in real output is, in itself, trivial, but the critical result is that energy consumption can be reduced without any cost in terms of total real output and total real income. The mechanism that secures this result is differential government policy--specific discouragement of energy use by means of taxes and specific encouragement of nonenergy intensive production and consumption by means of increased governmental provision of service activities.

The composition of production differs in ZEG from the technical fix pattern, due primarily to the impact of the new government expenditure. Agricultural and manufacturing output is reduced, transport and service output is increased. On the final use side the net result of the energy taxation and higher government expenditure is a relative increase in the proportion of government purchases in real GNP with an equal decrease in the share of personal consumption expenditure; investment and net exports are not affected. Real output and real income growth rates remain almost identical in ZEG and in technical fix growth. The composition of primary inputs does alter however. The energy tax and increased service purchases lead to an increase in labor input relative to capital input although both inputs show an increase in ZEG compared to technical fix growth.

The increase in labor input associated with ZEG is the result of energy-capital complementarity. Higher fuel prices lead to the substitution of labor for capital. Increased purchases of services leads to an increase in primary inputs, again with emphasis on labor input. Labor input in all nonfuel sectors increases, reflecting labor-capital substitution, while employment in service and government sectors rises substantially since increased activity in labor intensive sectors is superimposed on labor-capital substitution. Thus, total employment (labor input in manhours) is 1.8% higher in 2000 under ZEG than under technical fix growth. If all the increase in labor input were supplied by those previously unemployed, the unemployment rate would fall to 1.4%. But, the decrease in unemployment would probably be less as the additional labor would be supplied partly from longer work-weeks, partly from higher participation rates and partly from decreased unemployment.

Conclusions

The basic result of these economic analyses is the qualitative finding that substantial reduction in U.S. energy input, compared to the historical growth energy demand patterns, can be secured without major economic cost in terms of reduced total real output or reduced real incomes or increased inflation or reduced employment. The scope for inter-input substitution, for economizing on energy use and for redirection of demand patterns are such that the rate of growth of energy input over the remainder of this century can be more than halved without requiring fundamental changes in the structure of the economy and without requiring major sacrifices in real income growth.

Energy conservation, as represented by technical fix and zero energy growth conditions, will have an economic cost that is non-trivial. At the aggregate level the costs are that total real incomes and output are reduced e.g. the level of real GNP in 2000 is 3.5% lower under zero energy growth than under historical growth and that the rate of inflation is increased. The real GNP deflator increases at 3.8% a year under historical growth but at 4.1% a year under zero energy growth. However, energy conservation leads to increased employment so fears of widespread unemployment due to energy shortages are unfounded - once the economy has had time to adjust to more expensive and less plentiful energy, employment will actually increase as labor is substituted for capital and material inputs. There are also costs of energy conservation at the micro-economic level - new input patterns in production will require a relocation of some people and jobs in both geographical and occupational terms and people will have to adapt to new ways of doing things. The model does not spell out these very detailed effects, but it does show that, on the basis of economic responses observed in the past, such adaption is well within the bounds of practicability within the economic system as it is presently constituted.

The opposite side of these economic costs is the marked reduction in energy usage that is possible over the remainder of the century. The benefits from reduced energy usage are reduced environment degradation, reduced pollution, reduced dependence on foreign sources for a critical economic input, reduced need for nuclear and other energy sources whose full implications are, as yet, incompletely known, slowing the rate of depletion of U.S. fuel resources and so on. These benefits are fully explored in other Energy Policy Project studies. The present study demonstrates that these benefits can be obtained, admittedly at a cost, but not at the cost of major economic dislocation. In fact, the present projections indicate that economic activity can grow along a broadly similar pattern to that experienced in the past while simultaneously achieving major economies in energy consumption.

We conclude this study by pointing out that:

(i) energy conservation along the lines of technical fix or zero energy growth ideas is possible within the existing structure of the economy;

(ii) the cost of reduced energy use in terms of higher inflation and reduced real incomes and output are significant but not catastrophic;

(iii) these costs have been quantified above so that the costs and benefits of energy conservation can be explicitly faced and compared. This information can provide the basis for a rational choice regarding energy policy in the United States.

Discussion

One participant first made the comment that the introduction of price considerations in the determination of input coefficients is the major innovation of the paper. Then he stressed that it is not surprising that the model does not come up with a great change in GNP growth rates for varying scenarios, such as zero growth rate in the energy field, because it can be seen from the paper that the elasticity of cost with respect to changes in energy prices is very low. Finally, he asked whether it is really worthwhile going into great detail in fitting an energy model into an overall economy model and if it would not be better to specify the energy sector in greater detail and then analyze the different choices within the energy sector only. Mr. Jorgenson replied that it is very important to have a detailed energy sector because in addition to the policy analysis in this sector, there are many other policy questions that might be analyzed; these involve the effect of environmental restrictions on productivity in the electricity generating sector, which would in turn affect the price of electricity and would ultimately generate a reorientation of the energy sector within the total economy. So it is important to have a detailed representation of the energy sector within the total economy. Thus the question is, how much detail is needed for the other parts of the economy? On that Mr. Jorgenson argued that the degree of detail outside the energy sector ought to be essentially keyed to the need of policy analysis. Then Mr. Jorgenson came to the question of why they do this kind of modelling within an economy-wide model and why they do not isolate the energy sector and concentrate on that. He mentioned that the whole inter-industrial model is driven by the economy-wide analysis because all of the components of the final demand depend on growth trends. And the prices of the factors of production that determine the inter-industry structure depend on growth trends. Thus one cannot get an adequate conception of how the environment converts the energy sector until one has a clear picture of how those trends are likely to evolve. Finally, Mr. Jorgenson came to the question about policy analysis and whether one really needs to recompute the whole from the analysis in order to capture the inter-industry ramifications which are indicated in that model. And he said that the answer is "no". Therefore he stressed that the point of the questioner should be addressed to the use of such a model rather than the formulation. Then he noted that a comprehensive framework such as they have developed is essential for analysis, that some kind of detail on the non-energy sectors is also important, and that it may be possible to break off some pieces of this model and to analyze them separately.

Another delegate followed with two questions on the historical record of prices and quantities from which the demand relationships have been fitted. First, he asked if there are any relative prices of petroleum or electricity that are relative to other consumption goods within the range of the historical data. Finally, he asked whether it does not put quite a strain on the choice of the particular parametric representation of demand functions if these relative prices are not available. Mr. Jorgenson replied that the only data he can display for him are given in table 1; and there are dramatic changes in prices of energy relative to other things. Then he remarked that more than adequate historical data enable them to estimate these parameters in a reliable way. The delegate then asked about zero growth rate. Mr. Jorgenson replied that, in terms of the analysis, the prices of energy relative to labor fell by almost 50% over the period 1947-1971 and that price changes for zero growth are of the order of magnitude of 50%. And that 50% change relative to other things provides a very good way of resolving the components of change in these relative shares into the different price determinants.

Mr. Deam (United Kingdom) remarked that table 8, compared with historical prices, showed that the price of crude oil dropped to 3.5 and the price of refined oil went up to 28.5, for which he requested a technical explanation. Mr. Jorgenson replied that the basic mechanism they used is to assume that in order to achieve such a reduction one would have to impose a substantial tax on refined products. And the price is lowered as the demand for domestic crude oil drops and there is less to be supplied. Then Mr. Deam asked whether he had understood correctly in assuming that they are not determining price changes for petroleum products, but determining the price at which it would have to be set. Mr. Jorgenson replied that this is what they are doing.

Preliminary Presentation of the GLOSAS Proposal

G. Hough, T. Utsumi and E.A. Eschbach

Owing to the recent advancement of transportation and communication technologies, the peoples of the world have suddenly been brought into close physical contact with each other. These technologies now impinge in the most direct fashion on each individual, more so than at any other time in history. The countries of the world are, at most, 6-7000 miles apart--a few hours flight by jet and a few seconds by communication satellite.

Our world, with its limited natural resources and growing demands, appears to have shrunk. Industrial and technological advances have superseded national boundaries and have created a world community sharing aspiration for a "good life." These trends which force us into this community are different from those of the old bonds of agreements between nations; thus, the traditional regard for local territorial sovereignty is greatly reduced in force. Virtually all developing nations today aspire to achieve industrialization appropriate to their raw material sources.

Today nations of the world are becoming more intermeshed. In the past, we have attempted to make distinctions between localized or generalized problems and interacted world problems. With the interaction of the world's economies there is an ever-increasing tendency for regional and local problems to become world problems. The world's people are finding they are no longer able to escape to some new land (terra nova) to solve some irreconcilable problems of population pressure, different values, or a natural resource gap. The age of exploration has shifted from the discovery of new lands to the investigation of the social and technological consequences of our actions.

Today there are many major consumption blocks, namely Japan, Europe, Russia, and the USA, which draw heavily on the world's resources and products. Moreover, because there is significant interdependence, particularly among the industrialized nations, growth pressures in each of these blocks can combine to exacerbate pressures in the marketplace on resource development capability. Dominant material shortages such as energy, food and minerals are usually not foreseen with existing forecasting techniques. The consequences of shortages--in particular energy, food, and inflation--point to the need for gaining insight through modelling efforts that can treat the world as a whole, and yet accurately forecast interactions within nations without becoming overwhelmed by detail; nor can world problems any longer be addressed by words alone. A degree of quantification is needed. However, just because we have numbers and computer tape, we need not necessarily contribute scientific enlightenment to the world.

Forecasting with current trend techniques does not ensure foreseeing shortages in the future nor anticipating how households and interindustry consumers react in a shortage situation. Techniques to sense expert opinion as well as other sources are needed. Moreover, when consideration is given to the fact that many, rather than one or two, major material consuming economies in the world are involved, an international approach to modelling becomes necessary. Modelling at the world level requires degrees of aggregation which can lead to Malthusian oversimplifications. Even though the scientists involved have carefully qualified their work, the world forgets or chooses to disregard these qualifications, leading to a tendency to distort the deeper message of the modelling effort. The shortcomings of the uncorrected exponential growth curve can be circumvented by methods allowing interactions such as the introduction of decision makers into the loops. The system for introducing corrections to unfettered exponential growth necessitates developing a participative computing effort. A modelling effort on a world scale requires highly expert, detailed input on the part of specific industries and of nations. Many of the inputs of nations will be adversarial above and beyond business competition as they will be aggravated by concerns of national interest. The latter adversarial view is particularly important to developing nations who have a vital supply of but a single raw material for the developed nations. In the instance of the oil shortage, this is typified by the mid-east countries whose only material resource may be oil which, when depleted, could leave them with no further recourse. Resource-rich developing nations are responding in two ways: (1) raising prices and regulating availability of resources exported, and (2) taking steps to develop processing and manufacturing capabilities under their control (even if not within their national boundaries) to increase their share of the "value added" to resource materials. In addition, there are other resource examples subject to this syndrome, such as copper, platinum, chromium, and tungsten. Of great humanitarian concern is that some of the developing nations do not have sufficient major resources for export; thus their welfare, in turn, is immensely influenced by the efficiency of the developed nations converting ever more costly raw materials into industrial and agricultural products. Moreover, the developed nations' share of "value added" may be adjusted downward in many instances.

The specific goal of this proposal is to create a new international setting, using computers via satellite communication, in which we can examine worldwide problems such as the energy crisis, its ramifications, and other considerations. Computer conferencing will allow planners, students of decision making, and, utlimately, decision makers, the capability of interacting with their counterparts in all participating countries. By securing the reactions of other participants in a "controlled" setting, planners will be able to visualize the alternative critical path decisions with the help of programs in dynamic model form. The structured models as proposed will contribute to the identification of possible diseconomies of proposed solutions or perhaps the "next shortage," be it due to physical depletion, nationalistic interests, or both.

Satellite communications will serve as a mechanism to couple models and living data banks computerized for rapid response throughout the world. An overall autocratic master computer system is not necessarily visualized, but rather a distributed system, each node of which may have a special model of its own interacting with others. In conjunction with a small terminal and satellite communications, each distributed or decomposed sector would reflect the specific knowledge and aspirations fundamental to its welfare. Thus, the ultimate model may take the form of a central model as a means of fitting together the views and inputs of each major regional model, rather than the central model serving as an authoritative statement that often goes unheeded.

We have named this proposed effort GLOSAS, which in Greek conveys the meaning of "many tongues," and stands for Global Systems Analysis and Simulation. We proposed using a structured techno-economic model which: (1) is capable of identifying the next shortage condition, and then, (2) given a shortage condition, will evaluate alternative strategies proposed to minimize both the direct consequences of such a shortage and any secondary effects that could lead to another catastrophic condition. The modelling system employs an aggregated dynamic version of more detailed "reference" techno-economic models.

Currently in the United States, as a vital prologue to a much larger effort involving several years (Phase II), the research presented by this proposal (Phase I) will involve the following: (a) existing macro-energy models of the USA and Japan will be interfaced and operated via satellite communication network, and (b) an extensive proposal will be prepared for the worldwide effort of the project including securing the participation of essential expert and proponent groups.

In Japan the program is further along and interactive modelling has been established between Mitsubishi Research in Tokyo and several points in the United States, including Battelle-Northwest in Richland, Washington, and the University of California at Santa Barbara.

Finally, the Japanese and United States GLOSAS teams are pursuing fiscal and programmatic support, and soliciting the cooperation of interested parties and computer modeler throughout the world.

Discussion

Mr. Raiffa made the following comments: At present IIASA has a computing facility connecting us here in Laxenburg with a central processor in Cleveland, Ohio. We are connected from here to Vienna and from Vienna by dedicated lines to either Milan or Frankfurt and then by satellite to Cleveland, Ohio. And it does not work! The reason it does not work is because of the telephone lines from Laxenburg to Vienna. The other parts of it do work. So we are talking about a technology in this case which is not very far advanced. Maybe in ten years' time we will have a good telephone line from here to Vienna, so we can tie into this worldwide network.

One of the projects that we have in IIASA is a project on computer sciences, and we debated in great length on what we should be doing in various aspects of computer science including artificial intelligence, robotology, etc. We decided to postphone practically every effort except one in the area of the computer sciences project with the main thrust in the question of networking. Very difficult political problems are involved in networking between the Socialist and the non-Socialist groups of countries; however, we are pursuing this actively. The idea of satellite conferencing is on our agenda for exploration, so we would very much like to police what happens here and be informed of what goes on.

We recently had a conference sponsoring the work of Mesarovic and Pestel--they had a ten sector world model (one of the sectors being Japan, another sector being the Soviet Union, etc.) and they are actively pursuing the possibility that that model could be played in an interactive gaming way with terminals in different places. That is another aspect we will monitor but not be directly involved in.

REPORTS OF THE WORKING GROUPS

Each Working Group Report contains the following:

1. The possible topics proposed at the beginning of the meeting to initiate debate;
2. A summary of discussions which took place; and
3. The comments made at the Plenary Session on the reports prepared by each of the Working Groups.

Working Group 1: Methodological Problems of Energy Modelling (Projection, Optimization or Gaming Models) Report

Chairman: Mr. Manne, IIASA

Scientific Rapporteur: Mr. Sellinschegg, Karlsruhe

1. Possible topics proposed at the beginning of the meeting:

1) Trend extrapolation of individual variables versus projection of interrelated variables (such as quantities and prices).

2) What can be said about multi-criteria functions?

3) What are the relative merits of optimization and gaming versus simulation models?

4) Rules of thumb versus theoretical approaches.

5) How to construct the linkages between two or more optimization models?

6) Studying the sensitivity to parameter changes within the model versus effects of the specification error of the model.

2. Summary of the First Working Group Discussion Reported by the Chairman in the Plenary Session

I guess that our focus of attention is on two sets of things: one is something of which methodologists are fond--namely techniques--and the other has to do with criteria.

Let me first begin to talk about techniques. You recall that we were charged to consider the relative merits of applying simulation, optimization, and gaming for a variety of realistic problems. After a very short screening period we realized that most of the practical applications in the energy field tend not to be gaming models. We are not talking about models used in university research but the kinds of things that have been done at ministries and enterprises. Perhaps gaming models are taking place. They may refer to very highly confidential topics, but nevertheless these things are not reported by and large in the literature in a practical sense. What seems to be then the focus of most of these efforts is either simulation or optimization, and again one can detect some difference in the background of the people who tend to do one or the other. Engineers tend to like simulations because they enable them to describe situations that are probabilistic and discrete in a fairly realistic manner. Those that have come from economics or mathematics tend to bear a frame of thought which leaves them towards preferring optimization models. To some extent these are matters of taste; but to some extent you realize that once one specifies a simulation in which there are as many constraints as degrees of freedom, one can also interpret that as the outcome for an optimization model in which there are very few activities relative to the number of constraints; and so the optimization criterion makes very little difference. In fact there seem to be some elements of convergence that deal with discreteness, e.g. one could use linear programming or one could use dynamic programming. There may be some other situations in which discreteness and probabilistic considerations are combined, such as the loss of load problem in individual enterprises, and that seem to be favorite examples for the use of simulation rather than for analytical calculation of probabilities. So I should not say that we have reached a conclusion. Partly it depends upon the professional background of the people who do it. Partly it also depends, I suspect, upon the time perspective. The longer the planning horizon, the less relevant the details of the loss of load or the judgment of simulations may become; and perhaps the optimization model also becomes the more attractive. Perhaps from that very last remark you will realize to which of these two schools of thought I happen to belong. But I mapped reporting in a completely unbiased fashion. Obviously there are things that the one method can do which the other cannot do. Now one of the things that simulation can do immediately ties in with the second subject in an optimization model, i.e. one is required to state a criterion before seeing the computer printout. You cannot go into a computer with an optimal control or a linear programming or non-linear programming model without a priori specifying your preferences. Of course, that is the way it is described in the textbooks, but in practice there is interaction: you see the results of strategy model I, so you create strategy model II with a different criterion function. So again I am not so sure that the distinction is so completely clear-cut as one might think from posing the dichotomy between optimization which does require the advanced classification of a criterion function versus simulation in which there have to be as many constraints as there are degrees of freedom, and which do not therefore require the optimization function.

Now then, this immediately leads to the other thing which occupied the attention of our group yesterday: the question of multiple criteria. In practice we do not think that models are enough; we know that the practical man does not have at the back of his mind the case of taking demands as given and choosing ultimate means of supplies so as to satisfy those demands at minimum expected discounted costs. Rather, the decision maker has at the back of his mind some other criteria which are hard to specify, e.g. lives. If you really believe that nuclear technology costs more lives than some other technology, like solar, but you are not yet ready to be specific, i.e. to convert the cost in lives to a money cost, then you cannot quite apply the same criterion. So in practice it seems to be a matter of taste whether one optimizes one function subject to constraints (e.g. we do not want to kill more than 4,000 people by cancer each year, and we can do that either by diminishing sulphur dioxide emissions or by making plutonium accidents less likely where one can specify criteria which minimize discounted costs subject to killing no more than 4,000 people per year) or one tries to convert from the very beginning economic lives into costs. Here, perhaps, one does not like either of these approaches. Perhaps one wants to try interviews with decision makers. The whole idea of a multiple criteria function, then, does involve interview methods which social psychologists seem to know a lot more about than most of the rest of us. Among the behavioral scientists definitely missing at this point at IIASA are the social psychologists who have experience in these interviewing techniques (and you know how difficult they are). I do not think we should kid ourselves that this discount rate for a long term can simply be established in a one-hour interview. They may arrive at some number which may be ten percent per year. But nevertheless, one would like a more formal justification of this kind of perception because psychological interviews are obviously a rather treacherous territory.

As I say, we did not come to any conclusion that one should always use gaming, that one should always use optimization, or that one should always use simulation. But I think we were struck by similar questions about the different methodologies that came from different countries. The questions were not that we do it one way in the East or another way in the West. Obviously there are many different ways of doing these things, both in the East and in the West.

3. Comments

Prof. Raiffa:

The methodology group here has been wrestling with this type of issue: Problems between optimization, simulation, problems of gaming, problems of multiple criteria. The methodology group has worked very closely with the group in ecology and environment to consider one specific problem where these issues could be addressed. We call it the budworm problem here, and we are now in the process of producing a thick volume of which early drafts should be ready in about a month from now. Let me just say roughly what the issue is: the environmental group looked for an ecological problem where the modelling aspect was very well understood, where there were lots of statistical data and where the modelling in terms of simulation of an environment was very, very clear. They came to IIASA with a group of such models and looked for a means of coupling the ecological modelling with some sort of management policy organization or some other optimization programs, and the group decided to work on a problem in the Canadian forest. It is an ecological model involving balance between three spans of trees--the fir tree, the balsam tree and the spruce tree--and they have an ecological fight, the ususal kind of ecological model: The forest is attacked by a budworm and a budworm hits the different kinds of trees differentially. The budworm usually is at a low level and every 50 years or so it has a big spurt and there is an epidemic. Like most ecological models it is complicated because when you have a policy in one area there is a contagion effect from one area to the other. This model involved 250 regions. The question is what should be the regimen for spraying, cutting and management of this forest area. Now, George Dantzig and a group of people have worked very hard for months on very complex linear programming and nonlinear programming, integer dynamic programming and methods of optimization for that model. Their latest foray is in the question of trying to come to grips with those vexing problems involving trade-offs between economic considerations: what happens to the lumber industry and what happens to the preservation of wild life, problems of recreation, etc. So in this sort of microcosm we have all these issues being thoroughly investigated and I think the book, once it comes out in a preliminary issue in about a month, should be fascinating.

Working Group 2: The Formulation of Demand Relations in the Energy Field
Report

Chairman: Mr. Koopmans, IIASA

Scientific Rapporteur: Mr. Charpentier, IIASA

1. <u>Possible topics proposed at the beginning of the meeting</u>:

1) For which purposes to study demand for energy:
    at the macro level?
    at the micro level?

2) At the micro-economic level: What kind of other variables could be considered in addition to - prices - income - past trends?

3) What can be said about the notion of price elasticity of demand?

4) What are the effects of physical, technological and economic substitution possibilities on the demand for specific fuels?

5) Why are input-output matrices in energy terms so little developed?

6) Is the correlation between GNP and energy consumption a structural characteristic of the economy?

7) Is GNP a suitable variable for describing the degree of economic development?

8) Is it possible to use the same form to study the evolution of demand in developed countries and in developing countries?

2. Summary of the Second Working Group Discussion Reported by the Chairman in the Plenary Session

The assignment of our working group was the formulation of demand relations in the energy field. I shall try to employ some kind of telegram style in going through the successive points of our discussion.

The first point was exogenous versus endogenous representation of demand in energy modelling. I think there was some kind of agreement that the exogenous concept of demand is used a great deal, but should be looked at as some kind of first approximation that you may find useful. If you concentrate on something other than demand as the thing that should go into that model in more detail, then an exogenous notion of demand may well be useful. There is an example in the series of reactor strategy models of Häfele and Manne. Number 4 of this series still has exogenous demand and, as I understand it, number 5 will have a demand depending on price.

The second question was: Is the GNP-energy demand correlation one way to make demand endogenous, and is that really a structural relation? On that, I think, we concluded that GNP really is a proxy for consumers' income, and that therefore in a more detailed and sensitive representation of demand one would prefer to use an income variable, at least for household demand. For the industry demand one would then prefer to use a variable that is more specific to the energy use by that industry than GNP is; but, if you make cross sections over countries in which GNP is the main information available, then that will be a stand-in for that purpose. The next variable that one would introduce after income would be in the first place the price of energy, or of the component of energy that is at issue, and again for a third approximation the prices of other items of expenditure. In this case, if the study concentrates on one component of energy, then the prices of other components of energy would be good variables because they represent substitutes in consumption. To most of us, I think this was a thing on which we were in agreement, as this was familiar ground. Something that until quite recently was unexpected by me (but when I did suspect it I received confirmation from Prof. Jorgenson) concerns the strong implications of a hypothesis that is often made by economists. That is the hypothesis that the consumer maximizes utility under a budget constraint. That is, one postulates that either the individual consumer or some "representative" consumer maximizes a function of the quantities of the various goods or services he consumes and one may call that a utility function. The consumer also confronts given prices that he cannot influence and makes his choices within a given income or total expenditure figure. Then we can make the assumption that, as these prices vary and also as the income varies, the consumer will come out at that point where he reaches the greatest utility that is available to him, subject to those constraints. Now the implications of that assumption for demand analyses seem to be quite strong with regard to the price elasticities of demand. Let me just write down the definition of that notion: If the demand function is $q_i = f_i(p_1, p_2, \ldots, I)$ where q_i is the quantity demanded if the p_j are prices and I is the income, then the elasticity of demand for good i with respect to the price of good j is defined as the dimensionless quantity

$$\frac{p_j}{q_i} \cdot \frac{\partial q_i}{\partial p_j} \; .$$

Suppose you now make the assumption that this demand function itself arises from utility maximization, and in addition to that you assume that for different price constellations and different incomes

$$\frac{p_j}{q_i} \quad \frac{\partial q_i}{\partial p_j} = \eta_{ij} \text{ is constant for all } i,j.$$

The temptation to make that assumption is strong, because then you can say here is a parameter that means something, and if I fit a function with constant price elasticity I have some kind of a summary of the elasticity information that the data give me. However, it turns out that if this demand function does come from utility maximization then

$$\frac{p_i}{q_i} \quad \frac{\partial q_i}{\partial p_i} = -1 \text{ for all } i,\ j \text{ with } i \neq j.$$

This implication of utility maximization on the part of the consumer means that you have to give up either the utility maximization assumption, or else the elasticity concept as something that you can apply as a constant to a whole region. It is something that at best applies to a neighbourhood of a particular point. Some reflection shows that it could not apply to the whole region: Suppose the elasticity of demand for energy remains indefinitely less than 1 even when you continue raising the price of energy. Then at some point your whole budget would be taken up by energy expenditure alone, and that is not believable.

I now continue with another question: whether the response of demand to price is instantaneous. It certainly is not, and definitely not in energy. First of all, habits have to be modified and that takes some time. As long as the consumer thinks that he still wants the same amount of energy when it has become more expensive, he will find that he can only have less of something else. When he becomes aware of that he will change his habits. But in addition there is his energy-using equipment: e.g., the big car. It takes a few years before the big car is worn out, that is, before he is ready to substitute a smaller car for the bigger one. And therefore we must also regard these demand relationships particularly in the energy field as having a time lag structure to them.

One other item has to do with the aggregation of energy variables both in demand analyses and in supply analyses. A particular form of aggregation that is in rather widespread use is to reduce everything to Btu's, either Btu's of coal, Btu's of oil or on the consumer side Btu's of electric energy, and so on. There is a paper by Ralph Turvey* that recommends not to use what seems like the suggestion given by nature in the law of conservation of energy, but to regard the aggregation of demand as an economic problem. Turvey's proposal is to deal with the choice of a quantity index just like one would in the case of food or in the case of other components of consumption. Take the quantities consumed at various times of the various components, weight them by base year prices, and thus form a quantity index number as one would do for any other aggregated consumption variable.

There were two more items that went beyond the discussion of demand, but they did come up naturally from the discussion. One was the question by Mr. Krymm on optimal demand or as he revised it in the light of the discussion: "If you have an equilibrium model because demand is endogenous, then you would have demand equal to supply (call it quantity): then what is the optimal magnitude of that equal number?" This led to a discussion of the economic ideas on what are optimal outputs of various enterprises that are often administered on a national scale, like national electricity authorities, and to the discussion of average cost prices versus marginal cost pricing. Average cost pricing for an enterprise that works in the public interest is not a bad idea. But there are certain industries in which as the total output increases the extra cost of providing for an extra unit of demand diminishes. These industries are called decreasing cost (or increasing returns) industries, and we had some discussion of what is the optimal supply in that case. The traditional economic doctrine says that in those circumstances one should really price only at the extra (or marginal) cost occasioned by the last unit of demand. But this means that then the total cost of the energy supplying utility cannot be met from the total revenue. An argument would have to be made that in the public

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*Turvey, R. and Nobay, A.R. "On measuring energy consumption." Economic Journal, December 1965, pp. 787-93.

interest the deficit be made up rather by taxation than by raising the price (as would occur if one went over to average cost pricing). This is a very hard argument to make to any legislature, so it is not really explicitly adopted. However, as Mr. Janin explained, the Electricité de France in some--one might say roundabout--way comes close to it as a result of continuing inflation. We did not achieve a quantitative verification of that statement in our discussion but the observation is an interesting one.

Finally Mr. Aubauer brought up the very important question of environmental effect, and I am sorry that, at that point, time was limited for us to discuss it. One could really say that environmental damage is a form of negative demand. Therefore it affects the utility of the consumer and should come into the analysis just as much. One way in which that can be incorporated in the model is to set standards and estimate the extra cost of meeting the standards.

Working Group 3: How to Account for the Impact of the R & D Effort in New Technologies? Report

Chairman: Mr. Grenon, IIASA

Scientific Rapporteur: Mr. Weyss, IIASA

1. Possible topics proposed at the beginning of the meeting:

1) Is it possible to model the R & D effort?
2) How to model the relation of R & D inputs to the probabilities of success?
3) How to model successive goals and sequential conditional probabilities of success?
4) How to model game aspects of major technological choices?
5) What are subjective probabilities? Is this notion valid and useful for decision making?
6) How to take into account renewable resources such as solar and geothermal energy? Could we regard them as the income from an inexhaustible capital?
7) Could the new technology problems be taken into account and formulated in the same way for both developing and developed countries?
8) Who are the decision makers?

2. Summary of the Third Working Group Discussion Reported by Mr. Weyss in the Plenary Session

2.1 Is it possible to model the R & D effort?

Concerning the question as to the possibility of modelling the R & D effort there are several aspects for the seven types:

← Increasing complexity and multidimensionality, therefore increasing need for modelling ←

	Research theoretical desk work	Research experimental work	Research design on drawing board	
basic	1 (BRT)	2 (BRE)	3 (BRD)	
applied	4 (ART)	5 (ARE)	6 (ARD)	7 routine development & construction

→ Increasing availability of input data and goals, therefore increasing facility to make a model. →

Projects which are closer to industries already in existence have an advantage over those for which there is an absence of existing enterprises at persent (e.g. nuclear reactors vs. direct thermal use of solar energy).

The participants have not given forecasting models that exist today for 1 - 7; what is known are attempts such as structural forecasting models, estimations, broad summaries and lists of R & D budgets, and some model aspects of PERT (Program Evaluation and Routing Technique) in the practice of the enterprise.

So it seems to be an inherent task for IIASA, in particular with the help of methodology, to introduce modelling in R & D planning in all seven sectors, e.g. by means of a practical manual.

The main aim of the energy modellists should be an exact formulation of which kind of R & D or which ranking of priorities to choose, in order to avoid the energy gap, which is otherwise to be foreseen.

2.2 How to model the relation of R & D inputs to the probabilities of success?

The R & D — Success System

is more complex than any other system because of the possible feedback of intellectual brain and the R & D process.

It was suggested to develop a retrospective analysis of a fully completed R & D project that either was successful or unsuccessful (examples are the development of synthetic rubber, the river cooling of power plants). Such "ex post" analyses could be highly instructive for future models.

2.3 How to model successive goals and sequential conditional probabilities of success?

Uncertainties so far have been expressed by a cone of dispersion of the data. It indeed seems necessary to have as many repetitions of computer runs of a computer program as possible, which include either a sensitivity study or continuously putting in improved data and, if necessary, even changed goals.

The participants' opinions varied between iteration periods of 5 years to annual or even more frequent repetition of all variables.

2.4 How to model game aspects of major technological choices?

Although reality shows that the success of competing ideas is decided by a sort of competition of their proponents--similarly to the free market economy situation--the use of game theory possibly could intrude into personal spheres. What was referred to in this context by the participants as game theory dealt only with international competition or competition of energy companies.

As there is a certain lack of available brainpower, there is a problem of modelling there, too, primarily to link together for discussion all persons who are experts in a particular field.

2.5. What are subjective probabilities? Is this notion valid and useful for decision making?

If objective factors are already available then it can be assumed that somewhere R & D is already under way. If a new beginning is to be made, one almost always will have to restrict oneself to subjective probabilities. In this case there may be a danger that the decision maker yields to the opinion of an isolated protagonist. It would be better to look for experts who hold different opinions so that a fairer evaluation can be reached.

On the other hand, if too many people (Delphi) or too many disciplines are consulted there is the danger of obtaining several opinions about success varying between 90% and 1% so that the calculated average promises always only medium success, no matter how good the project is. It was felt that final consumers' or end-users' opinion should be weighed relatively high.

Looking around in the world ("What do others do in such a case?") only leads to pseudo-democratic imitation. An isolated but good suggestion for new technology even with only a subjective probability of success should be given a first chance.

2.6 How to take into account renewable resources such as solar and geothermal energy? Could we regard them as the income from an inexhaustible capital?

The use of the daily sun radiation could be a final solution that entails no hazards. Its transportation via secondary energy carriers from the tropic or subtropic zones to temperate zones of large energy use could lead to climatological problems. One participant expressed his doubts as to the availability and inexhaustibility of other raw materials needed in the harvesting of this solar energy and the enormous amounts of energy needed to produce the initial equipment for that harvesting.

As far as geothermal energy is concerned, there are certain experts who doubt that geothermal energy that can easily or with some medium difficulty be extracted, will suffice to meet the overall demand of mankind.

2.7 Could the new technology problems be taken into account and formulated in the same way for both developing and developed countries?

It may be in the interest of prestige of the developing countries that an attempt should be made to establish the same equations and the same model programs for all countries, and then to insert for each individual case

1) their individual goals,
2) different scales,
3) suitable input data,
4) marginal conditions (according to the political environment).

Environmental prophylaxis, risks of technical or social "after-cost" should perhaps be calculated as a negative ("malus") versus all other positive benefits ("bonus") of the particular technology.

2.8 Who are the decision makers?

A) Governments,

B) Often the invisible, bureaucratic, interwoven organisms,

C) Heads of institutions,

D) Even the experts and inventors and product managers if their new proposals are convincing.

In reality, persons as catalyzers are often the decision makers. With increasing credibility of the input data a higher level of objective decision making will be reached.

3. Comments

Mr. Häfele:

That exemplifies the observation that modelling is concentrating on quantifiable parameters but many areas are not so easy to be quantified.

Mr. Raiffa:

Throughout our various projects we looked at cross-cutting themes. One of the cross-cutting themes is technological assessment and I think from the methodological point of view we will be going into doing something of this kind.

Professionally, I, myself, have been involved in the uses of judgmental probabilities and expert opinion to make complex decisions. I was under the misapprehension that there was an ideological difference between the kinds of research done in the USA and some of the types of research done in the Soviet Union, but I have learned in my capacity here. I have been increasingly asked and requested by people from the Soviet Union to move more in the direction of the use of expert opinion and judgmental probabilities. In fact, there is Acad. Glushkov's institute in Kiev where they are dong a great deal of work on combining judgmental probabilities and expert opinion and this same topic that we will pursue.

This request came from the Academies of Sciences of both the GDR and from the CSSR, all pushing in the direction of the use of expert opinion in decision making; so we probably push in that direction in the methodology area.

As far as the strategies of research and development that you alluded to are concerned, the Energy Group is working in some kinds of problems about what are the optimum strategies for different agencies and governments in new technology. In addition, we have a project on Organizational Systems. One of the suggestions which came out from an international conference was that we should study "organizational ways for facilitating creative research in development strategies." And again, this was a suggestion that came out from both Socialist and non-Socialist sides together.

In addition, we have another project in the bio-medical area and we are trying to get some leadership here from Acad. Venediktov from the Soviet Union. He is a strong advocate of doing work on national strategies for research and development in the bio-medical area to make comparisons of global strategy efforts within nations and to couple that with questions of international strategy. He is particularly interested, as a concrete instance of this, to look at comparisons within each of the nations in oncological cancer research and what we can do in terms of an international community to coordinate our activities in this long range research and development effort and try to clarify some issues here. So this again is a theme which came up in the energy area but it is present in the other projects of IIASA.

Working Group 4: The Embedding of Energy Models into an Economy-Wide Model and the Linking of Several National and Regional Models Report

Chairman: Mr. Dantzig, IIASA

Scientific Rapporteur: Mr. Ponssard, IIASA

1. Possible topics proposed at the beginning of the meeting:

1) What techniques could be used?
2) What is the role of prices as links?
3) How to partition the world in such a way as to study the energy problem most efficiently?
4) What steps may be needed before we try to build a world energy model?
5) What is the practical meaning of a single-fuel model?
6) How to study coalition problems? Could the theory of games be useful?
7) Who are the decision makers in international problems? How does one model their role?
8) What forms of the objective function or functions are appropriate in international models?

2. Summary of the Fourth Working Group Discussion Reported by Mr. Ponssard in the Plenary Session

Topics discussed by the group:

1) Linkage of models with different forms of energy--regional considerations.
2) Linkage of models through transportation models.
3) Methodology for linkage of submodels (hierarchical systems, considerations of different objective functions).
4) Linkage of national oil and gas models.

Topic 4 received most emphasis because of the presence of Deam, Faidi (OPEC) and Clegg (BP) and also because this was certainly one sector in which there was strong interdependence between countries--in particular the uncertainty in the price of the Arabian oil in the last years made national models totally unrealistic.

Deam's international oil-gas model was then used as a basis for specific discussions and more general considerations. Since this model was extensively presented in a morning session, only comments will be reported here.

They may be summarized along these lines:

- the linkage of models ought to be different for a short or a long term horizon. Because of substitution possibilities less influence should be placed on price considerations for the long term; objective functions should also be different because of uncertainties;

- the price of Arabian oil is certainly not completely arbitrary but depends in fact on many criteria like the cost of raw materials, the cost of manufactured goods (in particular since some producing countries are engaged in heavy industrialization programs), the possibility of substitution. International models should reflect this interdependence (a discussion arose about the impact of the recent price increase on consumers' behavior; some persons thought that the 10% decrease in demand would level off quickly and not lead to any long term readjustment without political reinforcements).

The approach to the linkage of models through prices may put too much emphasis on a compromise for short term marginal costs whereas what one really needs today is to control the technological advances paying full attention to long term ecological and sociological aspects.

A second topic was also discussed: the methodological aspect of building multinational models. Reference was made to the Mesarovic/Pestel work using the theory of hierarchical systems. However, the general feeling was that there was no available satisfactory methodology to investigate multiple decision maker models. Existing methodology-like theory appeared as too difficult to implement and with a poor predictive power anyway, given the endogenous behavior of political actors; gaming has also a very poor predictive power through it makes (naïve) decision makers aware of new issues. Given the highly uncertain future and the difficulty of formally modelling the international competitive situation it was then re-emphasized that planning for flexibility at least offers a practical answer to this theoretical bottleneck. This may be achieved by developing good national models and introducing political constraints as parameters (e.g. taxes on oil, pollution standards, etc.). Then sensitivity analysis could be performed on these parameters and a short term strategy which would be fairly insensitive should be looked for. Such a strategy would then leave open the opportunity to benefit from the progressive resolution of uncertainty in the future.

3. Comments:

Mr. Häfele:

As originally envisaged we had planned to discuss future research topics in the field of energy modelling and to some extent the 4 research reports have illuminated this question. I would like to ask, though, whether, if they have been explicit, someone has a question or a point to make in general.

A participant:

There are three problems on which I think it advisable to work:

1. The study of inter-linkage between budworm systems and the energy system, not over the next 40 years, but over a number of years that is comparable to the time constant for ecological systems, about 500 to 1000 years.
2. Which is the optimal energy supply for an infinite time of use (i.e. that is optimal for a time period of one or two thousand years)? This does not at first sight seem to be a realistic problem, but it only appears to be that way, because, if you come into high rates of use, either you use solar energy and geothermal energy or you pile up so much waste that you have to give up the use of certain other kinds of energy.

3. The problem is not to minimize the occurence of failure of an energy system but to minimize the cost of failure of an energy system. This problem originates because the cost of failure of reactors is becoming very high and put a very high demand on the research capability of institutions and also on the infallibility of humans and of social systems. We are not accustomed to that, since we have not experienced such a problem historically; due to this fact it would be more optimal to find energy systems which can fail, yes, but of which the cost of failure can be absorbed by society.

Conclusion of the Energy Project Leader

W. Häfele

Some of you may be under the impression that mathematical modelling of energy demand and supply, as discussed during these two days, is the major thrust of the energy project. That is true only to some extent. To put this effort into perspective I would like to give you the background of the energy project.

1- Evaluation of strategies for a transition from fossil to nuclear fuels. (This project by Manne and Häfele is due to be completed shortly but there may be follow-ups.)

2- Heuristical attempt at a comprehensive description of the nuclear option (almost complete--largely involves expectation values but will employ utilities theory).

3- Solar option and identification of possible strategies, considering expected side effects and a balanced approach.

4- Use of utility theory for a comparison of those two options, with the aim of identifying the substance of that particular comparison and of establishing the method of comparing things that generally cannot be compared.

5- Investigations into the climatic effects and the identification of the interface between energy and water; i.e. largely a question of the moisture cycle in water and of sensitive spots on the globe suited for establishing large primary energy parks.

6- Work on resources--study of price/amount relation and side effects not yet fully considered, e.g. the amount of waste and debris in harvesting shale oil, etc. (Cooperation with the International Atomic Energy Agency desired.)

7- Investigation of risks and standards: The methodological problem of how to deal with residual risks; the causal procedures giving rise to standards. Relationship between damage and pollution rates, and study of the question of public acceptance--as important an ingredient in technology development as is the design of a good transformer. (Cooperation with the International Atomic Energy Agency, and closely with the Ecology Project because of the methodological question of resilience parameters. Related activities could focus on an optimization function of maximum resilience.)

8- Study of the siting of nuclear power plants vis-a-vis industrial facilities and urban settlements in general, which leads to natural interfaces of energy and water and ecology and urban settlement. The effort of mathematical modelling of energy demand and supply can be seen against that background. This perhaps illustrates why such a sensor is badly needed; in fact, an adequate energy policy strongly needs to sense more fully the reactions of economic/environmental changes.

This brings us to the end of the two-day working seminar, and I thank you all very warmly for your attendance and vital contributions. I personally feel that I have benefited a lot, and I am very grateful that you have taken the pains to prepare for this conference.

Conclusion of the Institute Director

H. Raiffa

On behalf of IIASA I would like to thank the participants of this Seminar for their superb contributions. I found the papers fascinating and informative, and the discussions in the workshops lively and intellectually challenging. I would also like to take this opportunity to thank Drs. Häfele, Manne and Charpentier for their organizational skills in gathering here a fine representation of scholars interested in the important class of problems related to energy modelling. I also want to inform you that administrative arrangements for our conferences are handled by the Secretary of our Institute, Dr. Andrei Bykov, and his able assistant Miss Ilse Beckey. I am sure you will want to join me in thanking them.

IIASA is now about 20 months old, but our scientific activities began only a scant ten months ago. IIASA is a unique experiment in international cooperation--it is ovbiously the creation of governments that are interested in closer scientific ties in peaceful pursuits, but at the same time it is formally a non-governmental institution. We are, as you know, sponsored not by governments, but by academies of sciences or similar prestigious research institutions. And being a non-governmental institution we can probe issues that may be too delicate for official bodies to consider. We also can act on a time schedule that is the envy of intergovernmental U.N. agencies.

Quite frankly, no one of us knows exactly what we can and cannot do; what worldly issues are too delicate for this fledgling Institute to investigate. But we can experiment, and we can try to find that unique role and identity for IIASA that will best contribute to progress toward a better world in the future.

I feel confident that IIASA can play a significant role as catalyst, disseminator, broker and initiator of research ideas. In all these endeavors we must exploit our peculiar position. First, we are truly interdisciplinary; we should bring our various research projects closer together over time, and in so doing take an integrated, systematic approach to complex problems of global or universal importance. Second, throughout our history (both before and after our charter was signed), in planning as well as execution, we have had the inputs of specialists from socialist, non-socialist and mixed economies. Third, we can use the backing of the thirteen adhering institutions which support us to identify, and lure here, outstanding scholars from academia, from research institutes and from industry. Fourth, as we become more and more credible as a research institute in our own right, we should be able to cement bonds with other institutes in collaborative research efforts--we should be part of a world-wide research network.

I feel we are indeed fortunate in having Professor Häfele as the leader of our Energy Project. He has attracted here a truly international team of research scholars. This working conference has helped us in several ways. First, I believe we are fulfilling one of our aspirations: the effective dissemination of information; second, we have generated ideas that will influence our research program; but most importantly we have brought a group of scientists here from different cultures but with similar research interests, and some of the personal contacts made here in Laxenburg might flourish in the future.

In closing, let me thank each of you for taking time out from your busy schedules to participate in this Seminar. I hope that it was as rewarding for you as it has been for us. We sincerely hope that many of you will continue you contacts with IIASA.