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Cover

The front cover shows a photograph taken at night of Schloss Laxenburg, a former summer residence of the Habsburgs, which now houses the International Institute for Applied Systems Analysis (IIASA). The palace is located at Laxenburg, a small community 16 kilometers south of Vienna. The Federal Government of Austria, together with the provincial governments of Lower Austria and Vienna, have generously restored and adapted the historical buildings to the needs of IIASA.

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PREMIER ISSUE: ASPECTS OF ENERGY

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
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PREFACE

It is a pleasure to introduce the first issue of *IIASA Reports*. For those who are already familiar with the International Institute for Applied Systems Analysis, this journal will provide information at regular intervals about the scientific progress of the Institute. For others, the journal will offer the first opportunity to become acquainted with the research activities of a unique international scientific institution. We hope that it will encourage many to follow and join in the Institute's efforts to foster international collaboration, advance science and systems analysis, and improve understanding of problems of global and universal importance.

The title *IIASA Reports* was chosen with two meanings in mind. First, the journal is a compilation of selected IIASA Research Reports, which are also published by the Institute in separately bound form. Second, it is a medium by which the Institute reports on its work to the worldwide scientific community, thereby fulfilling its responsibility to make its findings widely known, and thus available for critical examination.

IIASA Reports reflects the wide interests of the Institute and its collaborating institutions. These include internationally important aspects of energy, food and agriculture, resources, environment, population, human settlements, technology, organization and management, industrial development, and regional development, as well as the methodologies useful for their analysis drawn from economics, mathematics, statistics, and the engineering and management sciences. Its fundamental concern is to bring the knowledge and methods of science and technology to bear on important national and international problems. And its commitment is to the development and dissemination of the craft of systems analysis to fulfill this goal.

On occasion, *IIASA Reports* will publish special issues in which the articles center on a single theme. For example, this inaugural issue concentrates on energy, a fitting choice, since this was the topic of the first project IIASA undertook when it began its research in mid-1973. Future special issues will center on such subjects as environment, population and settlements, food and agriculture, and methodology. Most issues will, however, be unified only by the common interest of the Institute in the several topics reported. This diversity is a characteristic feature and, we believe, a strength of IIASA, whose multidisciplinary staff provides the range of knowledge essential to the realistic analysis of practical problems.

IIASA Reports will also reflect the international sponsorship and staff of the Institute. The 17 National Member Organizations (NMOs) whose contributions form the principal support for IIASA are listed on the inside front cover, as are the members of the Institute's governing Council, which consists of one member from each NMO. While the majority of the Institute's staff and collaborating institutions are drawn from the NMO countries, there are also staff members from other countries, so that as many as 25 nations may be represented on the staff at any time.

The authors of reports in this journal will generally be current or former members of the IIASA staff; however, some may also be consultants or persons from collaborating institutions. The reports will always deal with work done at the Institute or in support of its research program. The eight authors of the five papers in this inaugural issue come from seven nations, of which five participate in IIASA's work through NMOs. Two of the coauthor pairs are international, and one is a husband-and-wife team. Half of these authors are still on the IIASA staff; the other half are alumni. We expect that future issues will be the result of a similarly diverse authorship.

The contents of each issue are the general responsibility of an Editorial Board that comprises the principal research leaders of the Institute with the Director as Editor-in-Chief. Their responsibility goes deeper than that of most editorial boards because the research reported in *IIASA Reports* is carried out under their leadership. Furthermore, each report is read by at least two independent referees in a review process conducted by the Executive Editor.

Not all IIASA Research Reports will appear in this journal; many will be published in other scientific journals and a number will appear in book form. However, selected abstracts of relevant IIASA work appearing in other publications will be included, as will brief reports on other IIASA activities (meetings, important visitors, collaborative agreements) and the activities of IIASA's NMO organizations.

It is our hope that *IIASA Reports* will contribute to the development of a common scientifically based understanding of problems faced by many nations and thus will serve the causes of peace and well-being for all mankind.

Jermen M. Gvishiani
Chairman of the Council

Roger E. Levien
Director

FOREWORD

While this inaugural issue of *IIASA Reports* was being prepared, the Institute was completing a major report summarizing the work of IIASA's Energy Systems Program (ENP) from its inception in 1973 to the end of 1979, *Energy in a Finite World: A Global Energy Systems Analysis.*

ENP's work is focused on understanding global energy systems in the broadest sense; it stresses the need to synthesize the many facets of the energy question. In the course of this work, it has become apparent that one can only come to grips with the energy problem by approaching it on many different levels simultaneously. Whereas these levels of approach typically differ widely from one another – notably in the degree of detailedness and the support they receive from traditional disciplines – their common ground is careful documentation, a central aim of the forthcoming ENP report.

It is not surprising then that, reflecting this learning experience, the energy papers in this inaugural issue of *IIASA Reports* acknowledge both the complexity of the energy problem itself and the variety in approach taken at the Institute. They are selected not only from the ENP work, but also from that of the System and Decision Sciences, and Management and Technology areas.

The spectrum ranges from a Swedish case study considering a no-energy growth policy in a small open economy (Bergman), through input–output investigations of the impact that energy investments may have on an economy (Kononov and Por), a macroscopic description of the structural evolution of energy systems by way of an invariant logistic learning curve (Marchetti and Nakicenovic), and the specific aspects of the energy demand in a developing country such as India (Parikh and Parikh), to the problems of solar power in Europe (Bell).

If one disregards the naturally stronger coherence among the contributions by members within one group, such as the Energy Systems Program, one discovers that the contrasts among the individual articles are indeed considerable. Differences in time frame, methodology, emphasis on alternative energy options, the energy–economy relationship, and scope of applicability are all apparent.

This spread is intended. The step to take from here is to appreciate the fruitful discussion and interaction that the plurality of scientific inputs may stimulate within IIASA and outside the Institute. It is hoped that, in this way, the diversity of political, social, and economic viewpoints held by IIASA's scientists from many nations will help to foster the advancement of knowledge in the field of energy. To achieve this will reiterate the importance of IIASA's function of serving as an international platform for the exchange of scientific thought.

Wolf Häfele, *Deputy Director*
Program Leader, Energy Systems Program

ENERGY POLICY IN A SMALL OPEN ECONOMY: THE CASE OF SWEDEN

Lars Bergman

SUMMARY

In a small economy with a relatively large foreign trade sector, producers to a large extent must take as given prices on the world markets for goods and services. This means that the sectoral structure of production and employment is relatively sensitive to measures affecting domestic prices. For this reason some special problems are connected with economic policy in a small, open economy.

If such an economy plans to carry out an independent energy policy, aiming at a reduction in the growth of energy consumption, it faces at least two kinds of vexing trade-off problems. First, this energy strategy might have a negative impact on economic growth, that is, the energy policy might have a nonnegligible cost in terms of GNP or aggregate consumption growth. Second, a significant share of the reduction in energy consumption might be due to changes in the commodity composition of foreign trade, and thus in the sectoral structure of the production system. Thus the energy strategy might lead to a marked sectoral reallocation of the labor force, possibly combined with regional reallocation of the population. Such an outcome may not only cause difficult readjustment problems for industrial policy, but can also be in conflict with established goals related to regional development.

In this paper a multisectoral model of economic growth is developed and used for analysis of the economic impact of an energy strategy proposed by the Swedish government. According to the proposal, Sweden should aim at reducing energy consumption growth from a postwar average of 5% per annum to 2% per annum between 1973 and 1985 and to zero growth thereafter. The approach in this study is inspired by Professor Leif Johanson's so-called MSG-model of the Norwegian economy.

Here the model has been adapted so as to be useful for analyzing the problems on which this study is focused. Thus the model allows substitution between energy and other factors of production, and it has explicit export and import functions.

The model is based on input-output data for Sweden. As far as possible the numerical values of various parameters in the model are based on econometric evidence. In many cases, however, such evidence is not available and the author had to rely on reasonable "guesstimates". The projections presented in the report should thus be regarded as tentative rather than precise forecasts. However, the sensitivity of the results with respect to key assumptions has been investigated in detail, and therefore rather firm conclusions can be reached about the main results. The analysis was carried out for the period 1980 to 2000. The development of the economy in two cases was compared. In the first case there was no constraint on energy consumption growth. In the second, in line with Swedish policy, the growth of energy consumption was kept at 2% per annum between 1980 and 1985 and at zero growth thereafter.

The results indicate that, for the 20-year period studied, the target energy consumption growth rate can be attained without significant costs in terms of GNP or aggregate household consumption losses. The loss in GNP due to the energy policy was only about 1% at the year 2000. In addition, the energy policy did not lead to significant changes in the sectoral allocation of the labor force. This is because it was primarily capital, available as a result of the reduced growth of the capital-intensive energy sector, that was used as a substitute for energy in the production sectors. However, the negative impact on economic growth increases over time. If the energy consumption is kept at the 1985 level for 5 or 10 more years, the reduction in the rate of economic growth tends to be substantial.

The model simulations were carried out under the assumption that the net savings ratio in the economy remains constant over the period in question. Since one effect of the simulated policy measures was that profits tended to decrease, this assumption might seem dubious. The tendency towards falling profits might lead to a reduction in the net savings ratio. In that case the proposed energy policy has an additional indirect impact on economic growth.

In the model economy the target energy consumption growth rate was attained by means of a tax on energy consumption. At the year 2000 the tax rate, which kept energy consumption at the target level, varied between 137% and 871%, depending on the assumption made about the elasticity of substitution between energy and composite capital–labor. Energy tax rates of this order of magnitude would obviously create economic incentives for the development of new energy sources and energy conservation methods. It is quite possible that a number of R & D investments in these fields would turn out to have a high rate of return. That is, by means of R & D investments the shape of the production functions would be changed so that the negative impact on economic growth of the energy policy would be mitigated and the tendency towards falling profits counteracted.

As expected, the proposed energy policy turned out to have a larger impact on economic growth, the lower was the elasticity of substitution between energy and composite capital–labor. This applied particularly on the sectoral level.

When the elasticity of substitution was assumed to be 0.50 in all sectors, neither the structure of the production system nor the commodity composition of household consumption was significantly affected. However, when the elasticity of substitution was assumed to be 0.10, attainment of the target energy consumption development was accompanied by significant changes in the commodity composition of household consumption. In addition the rate of reduction of industrial employment was increased by the energy policy measures.

Although reservations can be made, it seems that energy consumption in Sweden can be kept on the target development path proposed by the government at least during a period of 10–15 years without significant conflicts with other social and economic goals. Whether this is an "optimal", or justifiable, energy policy is another question, and beyond the scope of this study.

1 INTRODUCTION

In response to the oil crisis of 1973–1974 and increasing public concern about various side effects of energy consumption, a reorientation of Sweden's energy policy was initiated. In 1975, the general principles of a "new" energy policy were presented by the government and approved by parliament. Before the end of spring 1980 there will be a referendum about the goals and means of future energy supply in Sweden with a special focus on the use of nuclear energy.

According to the 1975 government proposal, Sweden's energy policy should aim to reduce energy consumption growth from a post-war average of 5% per annum to 2% per annum between 1973 and 1985, and to zero growth from 1990. However, this is not a goal in itself. The basic idea is that the energy system should be transformed so as to reduce its environmental impacts as well as the country's dependence upon imported fuels. This transformation should, according to the government proposal, neither conflict with important social and economic goals nor lead to dramatic changes in the electricity supply conditions. The above mentioned growth figures were regarded as a reasonable compromise between these considerations.

This study is an attempt to quantify the impact of such an energy strategy for Sweden on the rate and pattern of economic growth. The study aims at identifying potential conflicts between energy policy goals expressed as target energy consumption growth rates, and goals related to aggregate economic growth as well as to the sectoral allocation of production and employment.

During the last few years a number of analyses of the macroeconomic impact of various national energy strategies have been carried out. See for instance Hudson and Jorganson (1974, 1978), Manne (1977), Hogan and Manne (1977) and Ridker *et al.* (1977). A common feature of these studies is that they deal with the U.S.A., a large and relatively closed economy.

The Swedish economy, on the other hand, is small and has a relatively large foreign trade sector. In such an economy the producers are largely pricetakers on the world market for goods and services. Thus the demand for exports is elastic with respect to deviations between world market prices and domestic prices. The same applies to the demand for competitive imports, that is, imported goods that are also produced domestically. When net export demand is elastic and the foreign trade sector relatively large, the sectoral structure of the economy is relatively sensitive to measures affecting domestic prices. This means that domestic energy taxation might bring about substantial changes in domestic energy consumption by changing the commodity composition of foreign trade. At given world market prices such structural changes in the economy do not necessarily lead to reductions in gross national product (GNP) or similar aggregate measures. Thus, at least for some time, there could be a rather weak relationship between aggregate economic growth and energy consumption growth. From this point of view a small, open economy has, *ceteris paribus*, a wider range of energy policy options than a large, relatively closed economy.

On the sectoral and regional level the trade-off problems connected with domestic energy policy might be more difficult in a small, open economy than in a large, relatively closed economy. When the sectoral allocation of production is sensitive to domestic energy policy measures, this might also apply to the sectoral allocation of the labor force and, possibly, the regional allocation of the population. Such an outcome of the energy policy may not only cause readjustment problems for industrial policy, but can also be in conflict with established goals related to regional development. Whether the above mentioned energy policy goals for Sweden are compatible with other economic policy goals depends on the quantitative importance of these effects together with the effects on aggregate economic growth resulting from the implementation of the energy policy.

Due to inertia in the economic system, short- and long-run effects of energy policy measures are likely to differ. This is especially true when a change in energy policy is anticipated by only a fraction of those affected by the measures. Short-run effects may include increased unemployment and capital losses. In the long run, however, a wide range of energy strategies are compatible with full utilization of the economy's resources. Instead the energy policy measures primarily affect the efficiency of resource allocation in the economy.

In this study, only long-run effects of energy policy measurements are dealt with. That is, the estimated impact of energy policy measures refers to a situation where producers and consumers are completely adjusted to prevailing market prices. Energy policy measures are assumed to be gradually implemented and exogenous conditions are assumed to change smoothly over time.

The study is carried out by means of a numerically formulated multi-sectoral growth model of the Swedish economy. The model does not indicate "optimal" growth paths, but simulates the economy's development under certain assumptions about exogenous conditions. A number of "futures" of the Swedish economy are simulated. These "futures" are conditioned by two sets of assumptions. First, there are assumptions about exogenous conditions, such as world market trade and prices, domestic supply of capital and labor, as well as about the domestic energy policy that is adopted. Second, assumptions are made about various parameters in the model, such as the elasticity of substitution between energy and other factors of production, for which econometric estimates have not been available.

The report is organized in the following way: in Section 2 the structural equations of the model are presented. Section 3 deals with some aspects of the solution procedure and Section 4 with the empirical basis of the study. The results of the study are presented in Section 5. Section 6 contains a summary of the main results as well as some conclusions.

2 THE MODEL

The model used in this study is a so-called MSG model (Multisectoral Growth). This kind of model is sometimes referred to as the Leif Johansen Model (see Blitzer *et al.*, 1975, p. 100), since Leit Johansen (1959) introduced the special solution technique that makes numerically formulated general equilibrium models easy to handle. A somewhat refined version of Johansen's original model is used by the Norwegian Ministry of Finance for long-term forecasting purposes (Johansen 1974, 1977), and recently Restad (1976) developed an MSG model to be used for similar purposes by the Swedish Ministry of Economic Affairs. In addition, Førsund (1977) has utilized a highly aggregated MSG model of the Norwegian economy for analysis of energy policy issues.

Except for complementary imports, foreign trade was exogenously determined in Johansen's model. Moreover, the elasticity of substitution between energy and primary factors of production (capital and labor) was set equal to zero. Restad retained the latter assumption but made foreign trade an endogenous part of the model. However, the composition of aggregate exports was exogenously determined and so was the import share in the domestic supply of goods and services. A common feature of both models is that the change in the economy's aggregate capital stock and the labor force are exogenously determined, while the sectoral allocation of capital and labor is determined within the model.

In Førsund's model the elasticity of substitution between capital, labor and energy was unity. Foreign trade and aggregate capital formation were exogenously determined.

In the MSG model there is a nonzero elasticity of substitution between energy and primary factors of production, and elasticity may differ between various sectors. There are also explicit import and export functions for each one of the trading sectors. However, as in the above mentioned models, both the total capital stock and the total labor force are determined outside the model, while the sectoral allocation of these factors of production are determined within the model.

2.1 SECTORS AND VARIABLES

There are nine sectors in the model economy (see Table 1 below). The sector "basic processing industries" contains the mining industry, the paper and pulp industry, and the chemical industry. Sector 8, "capital goods", is a book-keeping sector where various produced goods are combined in fixed proportions. Thus the input–output coefficients of the capital goods sector define the composition of the economy's stock of real capital. There is only one kind of output from each sector, and each commodity is only produced in one sector. Thus the index "*i*" sometimes refers to "sector" and sometimes to "commodity *i*", the only output from sector *i*.

TABLE 1 Sectors of the model economy.

Sector	Code
Energy	0
Agriculture, forestry and fishing	1
Basic processing industries	2
Manufacturing industries	3
Transportation	4
Private services	5
Housing services	6
Public services	7
Capital goods	8
Households	C

Table 2 defines the variables and parameters of the model.

TABLE 2 Variables and parameters of the model.

A. Exogenous variables	
G	public consumption
N	total labor force
K	total capital stock
I	total net investment

TABLE 2 *Continued.*

D	target surplus (deficit) on the current account
P_i^w	world market price of commodity $i = 0, 1, \ldots, 5$, expressed in foreign currency
$\bar{P}_i$	world market price of complementary imports used in sector $i = 0$, expressed in foreign currency
B. Endogenous variables	
X_i	gross output in sector $i = 0, 1, \ldots, 8$
F_i	a composite capital–labor input used in sector $i = 0, 1, \ldots, 7$
X_{ji}	input of commodity $j = 0, 1, \ldots, 5$ in sector $i = 0, 1, \ldots, 8$
K_i	capital stock in sector $i = 0, 1, \ldots, 7$
N_i	employment in sector $i = 0, 1, \ldots, 7$
$\bar{M}_i$	input of complementary import[a] in sector $i = 0$
C_i	household consumption of commodity $i = 0, \ldots, 6$
Z_i	export of commodity $i = 1, 2, \ldots, 5$
M_i	import of commodity $i = 0, 1, \ldots, 5$
P_i	price of commodity $i = 0, 1, \ldots, 8$
W	index of the level of wages in the economy as a whole
W_i	wage rate in sector $i = 0, 1, \ldots, 7$
R	index of the net return on capital in the economy as a whole
R_i	net return on capital in sector $i = 0, \ldots, 7$
Q_i	"user cost" of capital in sector $i = 0, \ldots, 7$
V	exchange rate (units of domestic currency per unit of foreign currency)
O	household consumption expenditure
Y	real gross national product
C	total real household consumption
C. Parameters[b]	
a_{ji}	input of commodity $j = 0, 1, \ldots, 5$ per unit of output in sector $i = 0, 1, \ldots, 8$
$\bar{b}_i$	input of complementary imports per unit of output in sector $i = 0$
ρ_i	substitution parameter. The elasticity of substitution between energy and the composite capital–labor input in sector $i = 0, 1, \ldots, 7$ is equal to $(1 - \rho_i)^{-1}$
α_i, γ_i	distribution parameters for sector $i = 0, 1, \ldots, 7$
λ_i	rate of (neutral) technical change in sector $i = 0, 1, \ldots, 7$
σ_i	rate of change of world market trade with commodity $i = 1, 2, \ldots, 5$
δ_i	rate of depreciation of the capital stock in sector $i = 0, 1, \ldots, 7$
ω_i	index of the relative wage rate in sector $i = 0, 1, \ldots, 7$
β_i	index of the relative rate on capital in sector $i = 0, 1, \ldots, 7$
η_i	elasticity of the household demand for commodity i with respect to total household consumption expenditures
η_{ij}	elasticity of the household demand for commodity i with respect to the price of commodity j

TABLE 2 *Continued.*

ϵ_i	price elasticity of export demand
μ_i	price elasticity of import demand
A_i, B_i	constants in the production and demand functions, respectively
D. Energy policy parameters	
τ	general value tax (or subsidy) on energy
ξ_i	value tax (or subsidy) on energy consumed in sector $i = 1, 2, \ldots, 7$, C
T_i	$1 + \tau + \xi_i$
E. Notation conventions	
If H is a variable in the model, then $\frac{\mathrm{d}H}{\mathrm{d}t} = \dot{H}$ and $\frac{\mathrm{d}H}{H\mathrm{d}t} = h$	

[a]Complementary imports is meant to imply the import of commodities that cannot (or at least are not) produced within the country.
[b]Both parameters and exogenous variables are determined outside the model, the parameters being constants while the exogenous variables may change over time.

2.2 TECHNOLOGY

Gross output is a function of the input of a composite capital–labor input, energy and various intermediate goods. The elasticity of substitution between energy and the composite capital–labor input differ between the sectors, while the elasticity of substitution between energy and intermediate goods as well as between the composite input and intermediate goods is zero in all sectors.* The elasticity of substitution between capital and labor in the "production" of the composite input is unity in all sectors. Complementary imports (mainly crude oil) used in the energy sector cannot be substituted for other factors of production. Finally, there are constant returns to scale in all sectors.

Using the symbols defined in Table 2 the technology can be described in the following way:

$$X_i = A_i[\gamma_i F_i^{\rho_i} + (1 - \gamma_i)X_{0i}^{\rho_i}]^{1/\rho_i} \quad i = 0, 1, \ldots, 7 \tag{1}$$

The elasticity of substitution between energy and the composite input is equal to $(1 - \rho_i)^{-1}$.

Equations (2)–(4) make the description of the technology complete:

$$F_i = K_i^{\alpha_i} N_i^{1-\alpha_i} \mathrm{e}^{\lambda_i t} \quad i = 0, 1, \ldots, 7 \tag{2}$$

$$X_{ji} = a_{ji} X_i \quad j = 1, 2, \ldots, 5 \;\; i = 0, 1, \ldots, 8 \tag{3}$$

$$\bar{M}_0 = \bar{b}_0 X_0 \tag{4}$$

* Of course, this relationship, as well as those presented in the following subsections, are "true" in the model only. The applicability of the model is discussed in Sections 4 and 5.

2.3 PRODUCER BEHAVIOR

The producers in the private sector of the economy are assumed to maximize their profits, while the public sector minimizes its cost for a given level of public consumption. The profit in sector i, Π_i, is defined by

$$\Pi_i = P_i X_i - T_i P_0 X_{0i} - \sum_{j=1}^{5} P_j X_{ji} - W_i N_i - P_8 \delta_i K_i$$
$$- R_i P_8 K_i - V\bar{P}_i \bar{b}_i X_i \quad i = 0, 1, \ldots, 7 \tag{5}$$

By using (3) we can define P_i^*, the sum of value added and energy costs in unit production costs, for commodity i as

$$P_i^* = P_i - \sum_{j=1}^{5} P_j a_{ji} - V\bar{P}_i \bar{b}_i \quad i = 0, 1, \ldots, 7 \tag{6}$$

where the last term on the right-hand side is different from zero only for the energy sector. Moreover, for sector 8, the book-keeping sector P_i^* must be zero, which means that

$$P_8 = \sum_{j=1}^{5} P_j a_{j8} \tag{7}$$

By defining "user cost of capital" in sector i, Q_i, by

$$Q_i = P_8(\delta_i + R_i) \quad i = 0, 1, \ldots, 7 \tag{8}$$

the expression for Π_i becomes

$$\Pi_i = P_i^* X_i - T_i P_0 X_{0i} - W_i N_i - Q_i K_i \quad i = 0, 1, \ldots, 7 \tag{9}$$

Profit maximization implies that, in equilibrium, the value of the marginal product of each factor of production must be equal to its price. Moreover, when the level of output is fixed,* profit maximization is equivalent to cost minimization. Using the production functions (1), the composite input functions (2) and the definition of profit (9), the profit maximization conditions become

$$\gamma_i(1 - \alpha_i)\left(\frac{A_i F_i}{X_i}\right)^{\rho_i} = \frac{W_i N_i}{P_i^* X_i} \quad i = 0, 1, \ldots, 7 \tag{10}$$

$$\gamma_i \alpha_i \left(\frac{A_i F_i}{X_i}\right)^{\rho_i} = \frac{Q_i K_i}{P_i^* X_i} \quad i = 0, 1, \ldots, 7 \tag{11}$$

* In the public sector, gross production is exogenously determined.

$$(1-\gamma_i)\left(\frac{A_i X_{0i}}{X_i}\right)^{\rho_i} = \frac{T_i P_0 X_{0i}}{P_i^* X_i} \quad i = 0, 1, \ldots, 7 \qquad (12)^*$$

The formulation of the model implies that there is only one type of labor and that labor and capital can be moved between the sectors. This means that in equilibrium no intersectoral profit and wage differentials can exist. However, due to uncertainty, institutional factors, disequilibria, etc., such differentials are revealed by actual data. The sectoral profit and wage rates can be defined as functions of sectoral factors, β_i and ω_i, and the profit and wage rates, respectively, for the economy as a whole, so that

$$R_i = \beta_i R \quad i = 0, 1, \ldots, 7 \qquad (13)$$

$$W_i = \omega_i W \quad i = 0, 1, \ldots, 7 \qquad (14)$$

Both Johansen and Restad regarded β_i and ω_i as institutionally determined constants. A better approach would perhaps be to simulate an adjustment process where intersectoral profit and wage differentials are gradually reduced and then to take the final solution as a point of departure for the analysis of the impact of energy policy measures. However, that has not been done in this study. Instead β_i and ω_i are regarded as constants, reflecting institutional factors which remain unchanged during the simulation period.

2.4 PRICES AND HOUSEHOLD EXPENDITURES

By an appropriate choice of unit of measurement, domestic prices in the model economy become unity at the initial point of time.** The prices in the model economy are normalized so that the general level of prices is kept constant over time. Of course, relative prices may change. The normalization of the price level is carried out by means of the following equation:

$$\sum_{i=0}^{7} P_i X_i + \sum_{i=0}^{5} V P_i^w M_i + V \bar{P}_0 \bar{M}_0 = \sum_{i=0}^{7} X_i + \sum_{i=0}^{5} M_i + \bar{M}_0 \qquad (15)$$

The total real† household consumption is defined by

$$C = \sum_{i=0}^{6} C_i \qquad (16)$$

* By definition $T_0 = 1$.

** All flows of commodities are expressed as values, using the prices prevailing at the initial point in time.

† That is, the value of household expenditure measured by the prices prevailing at the initial point in time.

When prices are normalized by (15), it follows that there might be deviations between total real household consumption C and total household consumption expenditure O. The quotient O/C defines the "implicit consumer price index" of the model economy. The demand for each kind of consumer goods and services is determined by the market prices of all goods and services and total household consumption expenditure,*

$$C_i = B_i O^{\eta_i} (T_C P_0)^{\eta_{0i}} P_1^{\eta_{1i}} \ldots P_6^{\eta_{6i}} \quad i = 0, 1, \ldots, 6 \qquad (17)$$

2.5 FOREIGN TRADE

The demand for exports from sector i is basically determined by the world market trade with commodity i. However, the share of world market exports supplied by domestic producers is a function of the relation between the domestic price, expressed in foreign currency, of the commodity in question and the world market price of that commodity. Thus, the export demand functions can be written as

$$Z_i = Z_i^0 \left(\frac{P_i}{VP_i^w}\right)^{\epsilon_i} e^{\sigma_i t} \quad i = 1, 2, \ldots, 5 \qquad (18)$$

Since the model is fairly aggregated, the "commodities" of the model economy should not be regarded as individual products. Rather, they are commodity groups consisting of several different products which are either substitutes or complements to each other. This means that imported and domestically produced units of a certain "commodity" may not be perfect substitutes, and thus export and import of a certain "commodity" can take place simultaneously. Moreover, the share of imports in the domestic supply of a certain "commodity" is not completely elastic with respect to price differentials. Thus, the import functions can be written as

$$M_i = \frac{M_i^0}{X_i^0} \left(\frac{P_i}{VP_i^w}\right)^{\mu_i} X_i \quad i = 0, 1, \ldots, 5 \qquad (19)$$

2.6 CAPITAL FORMATION

In the model economy, the growth of the aggregate stock of real capital is an exogenously determined variable. The net investments in the economy as a whole are also determined exogenously. Obviously the

* It should be noted that demand functions of this type, i.e., with constant elasticities with respect to expenditure and all prices, do not satisfy the budget constraint identically. However, the quantitative effect of this discrepancy is not likely to be important.

assumption about the change in the capital stock cannot be made independent of the assumption about the level of net investments. The link between these two assumptions is discussed in Section 3.

2.7 EQUILIBRIUM CONDITIONS FOR GOODS AND FACTOR MARKETS

In equilibrium, there must be equality between demand and supply in the markets for commodities, savings, labor and foreign currency. Thus, the following conditions have to be satisfied:

$$X_0 = \sum_{j=0}^{7} X_{0j} + C_0 - M_0 \tag{20}$$

$$X_i = \sum_{j=0}^{8} a_{ij}X_j + C_i + Z_i - M_i \quad i = 1, 2, \ldots, 5 \tag{21}$$

$$X_6 = C_6 \tag{22}$$

$$X_7 = G \tag{23}$$

$$X_8 = I + \sum_{j=0}^{7} \delta_j K_j \tag{24}$$

$$\sum_{j=0}^{7} K_j = K \tag{25}$$

$$\sum_{j=0}^{7} N_j = N \tag{26}$$

$$\sum_{i=1}^{5} \frac{P_i}{V} Z_i - \sum_{i=0}^{5} P_i^w M_i - \bar{P}_0 \bar{M}_0 = D \tag{27}$$

2.8 DEFINITIONS

GNP is defined by

$$Y = C + X_8 + G + \sum_{i=1}^{5} Z_i - \sum_{i=0}^{5} M_i - \bar{M}_0 \tag{28}$$

and e_i, the energy input coefficients, by

$$e_i = X_{0i}/X_i \tag{29}$$

2.9 ENERGY POLICY

In the model economy, energy policy is carried out by means of an energy policy parameter T_i defined by

$$T_i = 1 + \tau + \xi_i \quad i = 1, 2, \ldots, 7, \mathrm{C} \tag{30}$$

where τ is a general value tax (or subsidy) on energy and ξ_i is a value tax (or subsidy) on energy consumption in sector i. The total domestic consumption of energy E is defined by

$$E = X_0 + M_0 \tag{31}$$

In some applications E is an endogenous variable; then τ is exogenous. In others E is exogenous, which means that τ is endogenous.

Obviously there are a number of additional energy policy measures available in the real world. For instance, the authorities can impose restrictions on the use of certain energy production technologies, regulate the emission of various pollutants, prescribe certain insulation standards for new houses, etc. Energy policy measures of this kind either change the shape of the production functions or make the range of feasible factor combinations more narrow than the range of technically feasible factor combinations.

As the model is formulated, it is easy to analyze the sensitivity of the solutions with respect to changes of the production functions. However, it is not very easy to know how a particular energy policy measure will affect the production functions. For this reason, the analysis in this study is confined to energy tax policy.

3 THE SOLUTION OF THE MODEL

3.1 GENERAL REMARKS

All the variables of the model can be regarded as functions of time. By solving equations (1)–(30) for a number of points in time, the evolution of the model economy can be described. However, since many of the equations (1)–(30) are non-linear, the solution of the model is not a trivial problem.

What Johansen did was to differentiate all the relations with respect to time, and express the model in terms of relative rates of growth at the initial point in time. Due to the functional form of the model's structural equations, a linear equation system was then obtained. This linear equation system can be written

$$A\psi = B\phi$$

where ψ is the vector of relative rates of change of the endogenous variables and ϕ the vector of relative rates of change of the exogenous variables. If the number of endogenous variables is n and the number of exogenous variables m, A is an $n \times n$-matrix and B an $n \times m$-matrix. Thus the equation system has a unique solution.

In the solution matrix $A^{-1}B$ the element on the ith row and the jth column shows the impact of a given rate of change of the jth exogenous variable on the rate of change of the ith endogenous variable. Thus for a given set of assumptions about the exogenous variables, expressed as a vector ϕ^k, the rates of change of the endogenous variables, the vector ψ^k, are determined.

However, in order to get the model in such a simple form, it is necessary to treat the values of the model's variables at the initial point in time as constants, while their relative rates of change are treated as variables. This is obviously valid only at that particular point in time.

Accordingly, Johansen confined his analysis to the "growth tendencies" of the Norwegian economy at the initial point in time. Restad (1976, pp. 103–108) used the same method to approximate the model economy's development over a number of years. Since Restad's approach was adopted in this study as well, it should be described in some detail.

Given a data base for the point in time t, compatible with all the equations in the nonlinear version of the model, the matrices A_t and B_t can be calculated. Using the solution matrix $A_t^{-1} B_t$ and a set of assumptions about the exogenous variables, the development of the model economy between t and $t + \Delta$ is determined. If H_t denotes the numerical value of the (exogenous or endogenous) variable H at t and h is the relative rate of change of H at t, the value of H at $t + \Delta$ is then calculated by means of the formula

$$H_{t+\Delta} = (1 + \Delta h)H_t$$

Using the resulting values of the model's variables at $t + \Delta$, the matrices $A_{t+\Delta}$ and $B_{t+\Delta}$ can be calculated. Then the solution matrix $A_{t+\Delta}^{-1} B_{t+\Delta}$ together with assumptions about the exogenous variables determine the development between $t + \Delta$ and $t + 2\Delta$. In this way it is possible to trace the whole development process over an arbitrary number of periods with the length Δ.

The problem is, of course, that the values obtained in this way for $t + \Delta$ may not be compatible with the nonlinear version of the model. Moreover, the bias can be expected to increase for each step in the solution procedure. However, the bias appearing in each step can be expected to be smaller when Δ is smaller. Intuitively it seems reasonable to expect the bias emerging in a projection over a time period of given length to be smaller when Δ is smaller. However, no systematic analysis of this problem has been carried out within the frame of this study.

Within the Norwegian Ministry of Finance a method for computation of exact solutions to the MSG-model has been developed.* It is based on the approach described above, but, by means of an iterative procedure, the solution obtained after each step is made compatible with the nonlinear version of the model. For $\Delta = 3$ years, the value used by the Norwegian Ministry of Finance, the bias turned out to be relatively unimportant, and the iterative procedure converged after a small number of iterations.

* See Johansen (1974, chapter 10) and Spurkland (1970).

However, this study has been carried out without access to a program for exact solution of the model. Instead Restad's approach was adopted. The length of the sub-period was set equal to five years, that is, $\Delta = 5$. After the first step, there was a difference between output, as determined by the production functions, and demand in the size order 1–1.5% in each of the production sectors. Although disturbing, this bias was regarded as acceptable.

Another point is that both the aggregate stock of capital and aggregate net investments are exogenous variables in the model. Obviously there is a relation between changes in the stock of capital and net investments; the numerical values of the exogenous variables k and i cannot be chosen independently. In order to make the values of k and i consistent with each other the following approximate but computationally simple procedure is adopted. Thus it is noted that

$$\frac{K(t+\Delta) - K(t)}{\Delta} \approx I(t)\left(1 + \frac{i}{2}\Delta\right)$$

Division by $K(t)$ yields

$$\frac{K(t+\Delta) - K(t)}{K(t)\Delta} \approx \frac{I(t)}{K(t)}\left(1 + \frac{i}{2}\Delta\right)$$

or

$$k \approx \frac{I}{K}\left(1 + \frac{i}{2}\Delta\right)$$

In the matrix $A^{-1}B$ mentioned above, two elements represent the sensitivity of the growth of GNP (the variable y) with respect to the growth of net aggregate capital formation (the variables k and i). Using the information contained in these multipliers, k and i can be chosen so that the net savings ratio, I/Y, remains constant over time.

3.2 THE LINEARIZED VERSION OF THE MODEL

Table 3 contains all the equations of the linearized version of the model, and in the Appendix the derivation of each individual equation is briefly described. Throughout Table 3, endogenous variables are written on the left-hand side and exogenous variables on the right-hand side. Capital letters denote the value of the variable in question at the initial point in time. The coefficients A_{ij} in equations M4 and M7 are defined by

$$A_{ij} = e_{ij} - a_{ij}$$

where e_{ij} is 1 when $i = j$ and 0 when $i \neq j$.

TABLE 3 The equations of the linearized version of the model.

Number	Equation	
M1 : i	$x_i - \frac{\alpha_i}{1-\alpha_i}\frac{\omega_i WN_i}{P_i^* X_i} k_i - \frac{\omega_i WN_i}{P_i^* X_i} n_i - \frac{T_i P_0 X_{0i}}{P_i^* X_i} x_{0i} = \frac{1}{1-\alpha_i}\frac{\omega_i WN_i}{P_i^* X_i}\lambda_i$	$i = 0, 1, \ldots, 7$
M2	$Yy - Cc - X_8 x_8 - \sum_{i=1}^{5} Z_i z_i + \sum_{i=0}^{5} M_i m_i + \bar{M}_0 \bar{m}_0 = Gg$	
M3	$\frac{P_0}{P_0^*} p_0 - \sum_{j=1}^{7} \frac{P_j a_{j0}}{P_0^*} p_j - \frac{V\bar{P}_0 \bar{b}_0}{P_0^*} v + (1-\rho_0) x_0 + \rho_0 \alpha_0 k_0 + (\rho_0 - \alpha_0 \rho_0 - 1) n_0 - w = -p_0 \lambda_0 + \frac{V\bar{P}_0 \bar{b}_0}{P_0^*} \bar{p}_0$	
M4 : i	$\sum_{j=1}^{7} \frac{P_j A_{ji}}{P_i^*} p_j + (1-\rho_i) x_i + \rho_i \alpha_i k_i + (\rho_i - \alpha_i \rho_i - 1) n_i - w = -p_i \lambda_i$	$i = 1, 2, \ldots, 7$
M5 : i	$\frac{P_8(\delta_i + \beta_i R)}{Q_i} p_8 + \frac{P_8 \beta_i R}{Q_i} r + k_i - w - n_i = 0$	$i = 0, 1, \ldots, 7$
M6	$\frac{P_0 - P_0^*}{P_0^*} p_0 - \sum_{j=1}^{7} \frac{P_j a_{j0}}{P_0^*} - \frac{V\bar{P}_0 \bar{b}_0}{P_0^*} v + (\rho_0 - 1) x_{00} - (\rho_0 - 1) x_0 = \frac{V\bar{P}_0 \bar{b}_0}{P_0^*} \bar{p}_0$	
M7 : i	$\sum_{j=1}^{7} \frac{P_j A_{ji}}{P_i^*} p_j + (\rho_i - 1) x_{0i} - (\rho_i - 1) x_i - p_0 - \theta \frac{\dot{\tau}}{T_i} = (1-\theta) \frac{\dot{\tau}}{T_i} + \frac{\xi_i}{T_i}$	$i = 1, 2, \ldots, 7$
M8	$P_8 p_8 - \sum_{j=1}^{5} P_j a_{j8} p_j = 0$	
M9	$\sum_{i=0}^{7} (P_i - 1) X_i x_i + \sum_{i=0}^{5} (VP_i^{w} - 1) M_i m_i + (V\bar{P}_0 - 1) \bar{M}_0 \bar{m}_0 + \sum_{i=0}^{7} P_i X_i p_i + [V\bar{P}_0 \bar{M}_0 + \sum_{i=0}^{5} VP_i^{w} M_i] v$	
	$= -\sum_{i=0}^{5} VP_i^{w} M_i p_i^{w} - v\bar{P}_0 \bar{M}_0 \bar{p}_0$	

TABLE 3 *Continued.*

Number	Equation	
M10:i	$c_i - \eta_i O - \sum_{j=0}^{6} \eta_{ji} p_j - \theta \frac{\dot{\tau}}{T_c} \eta_{0i} = (1-\theta) \frac{\dot{\tau}}{T_c} \eta_{0i} + \frac{\dot{\xi}_c}{T_c} \eta_{0i}$	$i = 0, 1, \ldots, 6$
M11:i	$z_i - \epsilon_i p_i + \epsilon_i v = \sigma_i - \epsilon_i p_i^w$	$i = 1, 2, \ldots, 5$
M12:i	$m_i - \mu_i p_i + \mu_i v - x_i = -\mu_i p_i^w$	$i = 0, 1, \ldots, 5$
M13	$\bar{m}_0 - x_0 = 0$	
M14:i	$x_{0i} - x_i - \dot{e}_i / e_i = 0$	$i = 0, 1, \ldots, 7$
M15	$\sum_{j=0}^{7} \frac{K_j}{K} k_j = k$	
M16	$c - \sum_{i=0}^{6} \frac{C_i}{C} c_i = 0$	
M17	$X_0 x_0 - \sum_{j=0}^{7} X_{0j} x_{0j} - C_0 c_0 + M_0 m_0 = 0$	
M18	$(1-\theta) Ee - X_0 x_0 - M_0 m_0 = -\theta Ee$	
M19	$\sum_{j=0}^{7} A_{ij} X_j x_j - C_i c_i - Z_i z_i + M_i m_i = 0$	$i = 1, 2, \ldots, 5$
M20	$x_6 - c_6 = 0$	
M21	$x_7 = g$	
M22	$x_8 - \sum_{j=0}^{7} \frac{\delta_j K_j}{X_8} k_j = \frac{I}{X_8} i$	

TABLE 3 *Continued.*

Number	Equation
M23	$\sum_{i=1}^{5} \frac{P_i}{V} Z_i z_i + \sum_{i=1}^{5} \frac{P_i}{V} Z_i p_i - \sum_{i=1}^{5} \frac{P_i}{V} Z_i v - \sum_{i=0}^{5} P_i^{w} M_i m_i - \bar{P}_0 \bar{M}_0 \bar{m}_0$
	$= \bar{P}_0 \bar{M}_0 \bar{p}_0 + P_0^{w} M_0 p_0^{w} - \sum_{i=1}^{5} P_i^{w} (Z_i - M_i) p_i^{w} + \dot{D}$
M24	$\sum_{j=0}^{7} \frac{N_j}{N} n_j = n$

It should be noted that the formulation of the model can be changed by means of the parameter θ.* When $\theta = 0$, the total energy consumption is endogenously determined while the general energy tax rate τ is an exogenous variable. When $\theta = 1$, however, the total energy consumption is exogenously determined, while the tax rate τ which is sufficient to induce that level of total energy consumption is determined within the model.

* See equations M7:i, M10:i and M18.

4 THE EMPIRICAL BASIS OF THE STUDY

Two kinds of data are needed in this study. The first is a complete description of the state of the economy in terms of intersectoral and final deliveries of goods and services, capital stocks, prices, etc. at a particular point in time. The second is estimates of the parameters of the production, household demand, export and import functions.

The data used in this study are primarily those prepared by the Ministry of Economic Affairs for the above mentioned study by Restad. The estimates of the intersectoral flows and other variables describing the state of the economy were obtained by means of an econometric model, used for forecasting the development of the Swedish economy between 1975 and 1980. Thus, the "initial year" in this study is 1980. In Table 4, some key figures from the data base are presented; the complete data base can be obtained from the author upon request.

In Table 5, the parameters of the household demand functions used in this study can be seen. With one exception, housing services, the figures are obtained from Restad (1976, p. 110) where the demand for housing services was treated as an exogenously determined variable. However, the price of energy is a relatively important determinant of the price of housing services (see Table 4), and changes in the consumption of housing services have a relatively large impact on the total consumption of energy. Thus, given the purpose of this study, it is not satisfactory to treat housing expenditures as an exogenously determined datum. Instead, it is, somewhat arbitrarily, assumed that the demand for housing services is unitary price and expenditure elastic.

In Restad's model there are no explicit export and import functions. Consequently the numerical values of the parameters in the trade

TABLE 4 Selected data about the Swedish economy, estimates for 1980.

Sector	Input of energy per unit of output[a]	Share of total energy consumption	Share of GNP originating in the sector	Share of exports	Share of employment	Share of capital stock
Energy	0.0418	0.0373	0.043	–	0.008	0.064
Agriculture, forestry and fishing	0.0418	0.0396	0.039	0.009	0.052	0.042
Basic processing industries	0.0509	0.1579	0.088	0.257	0.062	0.064
Manufacturing industries	0.0151	0.1678	0.353	0.630	0.289	0.135
Transportation	0.0348	0.0426	0.057	0.054	0.069	0.078
Private services	0.0254	0.0959	0.182	0.050	0.255	0.108
Housing services	0.1461	0.1902	0.067	–	0.006	0.359
Public services	0.0272	0.0829	0.172	–	0.260	0.150
Household consumption	0.0285[b]	0.1859	–	–	–	–

[a]Both energy and output are measured in terms of SKr at 1968 prices.
[b]Share of expenditures on energy in total consumption expenditures.

SOURCE: Restad (1976, pp. 132–133).

TABLE 5 Estimated price and expenditure elasticities of the household for consumer goods and services.

Demand for goods from sector	Elasticity with respect to . . .							
	P_0	P_1	P_2	P_3	P_4	P_5	P_6	C
0 Energy	−0.3373	−0.0671	−0.0768	−0.7444	−0.0613	−0.2050	0	1.4919
1 Agriculture, forestry and fishing	−0.0120	−0.1193	−0.0247	−0.1300	−0.0193	−0.0658	0	0.3711
2 Basic processing industries	−0.0310	−0.0557	−0.3125	−0.4919	−0.0280	−0.0648	0	0.9269
3 Manufacturing industries	−0.0228	−0.0541	−0.0469	−0.6778	−0.0375	−0.1253	0	0.9244
4 Transportation	−0.0299	−0.0537	−0.0614	−0.5955	−0.2291	−0.1640	0	1.1936
5 Private services	−0.0349	−0.0627	−0.0716	−0.6947	−0.0573	−0.4714	0	1.3926
6 Housing services	0	0	0	0	0	0	−1.0000	1.0000

SOURCE: Restad (1976, p. 110).

functions of the model used in this study could not be obtained in the same easy way as the parameters of the household expenditure functions. Unfortunately there was no other suitable study available. The "solution" to this problem was simply to assume a set of, seemingly, reasonable parameters and investigate to what extent the results were sensitive to the assumptions on this particular point. The adopted numerical values of the price elasticity parameters in the export and import functions are discussed in Section 5 in connection with the description of the so-called "base" case.

Except for the substitution parameters, ρ_i in eq. (1), the parameters of the production functions are obtained by using eqs. (10)–(12) and income distribution data. The determination of the numerical values of the substitution parameters is, however, a little bit more complicated.

During the last few years a number of studies of the substitutability of energy and other factors of production or between various kinds of energy have been carried out. Although these studies differ from the present one in terms of the specification of the production functions as well as the level of aggregation, some results can be used as a basis for assumptions about the substitution parameters in the model used in this study.

In a study by Berndt and Wood (1975),* based on aggregated time-series data for the American industry, capital and labor were found to be complements (that is, the estimated elasticity of substitution had a negative value), while energy and labor turned out to be substitutes. Similar results, but quite different values, were obtained in a study by Denny and Pinto (1975),** based on aggregated time-series data for the Canadian industry. To the extent that these results are valid, the specification of the production functions in the model used in this study is rather dubious.

However, in a study by Gregory and Griffin (1976),† based on a cross-section of data from nine different countries, both capital and energy as well as labor and energy were found to be substitutes. The estimated elasticity of substitution between capital and energy was close

* A homothetic translog production function, where output was a function of the input of capital, labor, energy and material, was used. The elasticity of substitution between each pair of inputs was estimated.

** A generalized nonhomothetic Leontief production function with capital, labor, energy and materials as inputs was used, and the elasticity of substitution between each pair of inputs was estimated.

† The same approach as in Berndt and Wood's study was used, but only three inputs, capital, labor and energy, were distinguished.

to 1.0 for all countries, while the corresponding figure for labor/energy was 0.8. Thus, to the extent that these findings are valid, production functions of the type used in this study can be justified. Moreover, the elasticity of substitution between energy and composite capital–labor input can be assumed to be positive and not much less than unity.

This is not a place for a detailed discussion of the merits and drawbacks of various studies in this field of econometrics. However, it seems more appropriate to base a long-run study like the present one on results obtained on the basis of cross-sectional rather than time series data.

Yet it is not reasonable to assume that the elasticity of substitution between energy and capital–labor is close to unity. This is because Gregory and Griffin's results apply to the industry as a whole rather than to individual sectors. Thus, part of the estimated substitutability is the result of structural change within the industry.* If these results are directly applied to individual sectors in a multisectoral model, the effect of structural change on energy consumption will be counted twice. Thus, even if Gregory and Griffin's results are accepted, the elasticity of substitution should be a bit less than unity on the sectoral level.

Apart from these considerations, the results obtained in Gregory and Griffin's study seem, intuitively, a little bit too "optimistic" in terms of the substitutability of energy and other factors of production. This statement is, of course, difficult to defend, but reference to Manne (1977, p. 10), who considers an elasticity of substitution between energy and capital–labor equal to 0.25 for the economy as a whole to be the "best" estimate, could perhaps be made.

Obviously there is not very solid ground for assumptions about the substitutability of energy and other factors of production. In this study the elasticity of substitution between energy and capital–labor is assumed to be 0.25 in the "base" case. In the so-called "rigid" case, the corresponding figure is 0.1, while it is 0.5 in the so-called "flexible" case.

* An attempt to estimate the impact of structural change on the change in energy consumption during a 10-year period is made in Bergman (1977).

5 RESULTS

In the first step of the analysis, a "base" case is calculated. To a large extent this case is based on assumptions made in a recent long-term economic forecast published by the Ministry of Economic Affairs (1975). However, since neither the functional form of the structural equations nor the numerical values of various parameters in the model presented above are tested against actual data, the base case should not be regarded as a forecast. Instead it can be said to represent a plausible, but not necessarily the most probable, development of the Swedish economy.* The basic issue in this step of the analysis is whether or not the growth of energy consumption is likely to be higher than the target growth rate put forward in the 1975 government proposal.

In the next step it is assumed that domestic energy policy is directed towards reducing the growth of energy consumption to 2% per annum between 1980 and 1985 and to zero growth thereafter. The impact of this strategy on GNP and other economic variables is calculated not only for the "base" case, but also for two polar cases: one where the technology is "rigid" in terms of energy input coefficients and one where it is "flexible".

5.1 THE BASE CASE

In the base case it is assumed that the net savings ratio remains approximately constant between 1980 and 2000. This means that the economy's

* In the terminology of Johansen (1977), the base case can be regarded as a "projection".

aggregate capital stock grows by approximately 2.0% per annum.* In accordance with the projections made by the Ministry of Economic Affairs, the labor force, measured in man-hours, decreases by 0.2% per annum between 1980 and 1990 and by 0.6% per annum between 1990 and 2000. On the same basis the growth of public consumption is assumed to be 2.5% per annum between 1980 and 2000.

The trade on international markets where Swedish producers compete is assumed to grow by 4% per annum during the entire period. Except for oil prices, world market prices, expressed in foreign currency, are assumed to remain constant in real terms. World market prices of crude oil as well as refined petroleum products are assumed to increase by 2% per annum in real terms between 1980 and 1990. For the period of 1990–2000 the corresponding figure is 5%.

No model of international trade flows has been available. Thus it has not been possible to test whether or not the assumptions made about world market conditions are consistent with each other.

As was mentioned in the preceding section, no estimates of the price-elasticity parameters in the trade functions have been available. It seems reasonable, however, to assume that the demand for imports is less price elastic than the demand for Sweden's exports. This is because a substantial part of Sweden's imports are complementary rather than substitutes to domestically produced goods and services. In accordance with the discussion in the introductory section, the demand for Sweden's exports should be quite price elastic. In particular this holds for standardized products like the output from "basic processing industries".

The specific assumptions made are the following: the absolute value of the price elasticity of the export demand for output from "basic processing industries" is assumed to be 3.0. The corresponding figure for "manufacturing industries" is 1.5, and 1.0 for the other exporting sectors.** In all import functions the absolute value of the price elasticity parameter is set equal to 0.5.

The last set of assumptions concerns the productivity of the combined capital–labor input.† Here the assumptions are based on the above mentioned forecast by the Ministry of Economic Affairs. Thus, in "basic processing industries" the productivity of composite capital–labor is assumed to grow by 3% per annum. For "agriculture, forestry and fishing"

* In the forecasts made by the Ministry of Economic Affairs, this figure was assumed to be 3%. Thus a gradual increase in the net savings ratio was assumed.

** That is, "agriculture, forestry and fishing", "transportation" and "private services".

† That is, the parameter λ_i in eq. (2).

and "manufacturing industries" the corresponding figure is 2.5%, while it is 2% in transportation and 1% in the remaining sectors.

The main results obtained in the base case are presented in Table 6, together with results from a projection denoted "rapid growth". This case differs from the base case with regard to the assumptions made about the productivity of the combined capital-labor input and capital formation. Thus, annual rates of change are one percentage point higher in the "rapid growth" case than in the base case. This means that the productivity assumptions in the "rapid growth" case are close to the actual productivity growth experienced in Sweden during the 1950s and the 1960s.

TABLE 6 Calculated annual change of selected macroeconomic variables, 1980–2000, percentage points.

	Base case	Rapid growth case
GNP	2.0	3.6
Real household consumption	2.8	4.4
Energy consumption	2.3	4.2
Industrial employment[a]	−2.6	−1.3

[a]That is, employment in "basic processing" and "manufacturing" industries.

In comparison with the experience during the period 1950–1972, the base case represents a reduction of the growth of GNP and, in particular, energy consumption.* Yet the level of energy consumption in the year 2000 is 43% higher than the level compatible with the target growth rate for energy consumption mentioned in the introductory section.

The growth of real private consumption is only slightly below the "normal" postwar figure. The declining industrial employment is a continuation of a postwar trend; labor productivity increases faster than production in industry and consequently the demand for labor decreases in that sector.

The increasing share of consumption in GNP is the result of a gradual improvement of Sweden's terms of trade in the base case. This outcome to a large extent depends on the assumptions made about the world market prices of industrial goods as well as the assumptions about the price elasticity parameters in the foreign trade functions. If, for instance, the world market price of the output from "basic processing industries" is assumed to decrease by 1% per annum in real terms rather than remain

* During this period the average annual growth rates for GNP and energy consumption were 3.6% and 5%, respectively. Thus the "energy intensity" of GNP grew by approximately 1.4% per annum.

constant, the growth of real private consumption is reduced by 0.6 percentage points per annum.

In the "rapid growth" case the growth of GNP is "normal" according to postwar standards. However, as in the base case the increase in the "energy intensity" of GNP is considerably slower than during the period 1950–1972. In order to discuss this result, it is appropriate to decompose the total base case change in energy consumption between 1980 ($t = 0$) and 2000 ($t - T$) into a number of components. The following identity is then utilized:

$$\underset{\text{TOT}}{E(T) - E(0)} = \underset{\text{VOL}}{\sum_{i=0}^{7} e_i(0)[\bar{X}_i - X_i(0)]} + \underset{\text{COMP}}{\sum_{i=0}^{7} e_i(0)[X_i(T) - \bar{X}_i]} + \underset{\text{INP}}{\sum_{i=0}^{7} [e_i(T) - e_i(0)]\, X_i(T)} + \underset{\text{DIR}}{[C_0(T) - C_0(0)]} \qquad (32)$$

where the variable $\bar{X}_i$ represents the hypothetical production in sector i if aggregate production is equal to aggregate production at $t + T$ and the composition of aggregate production is equal to the composition of aggregate production at $t = 0$,* and TOT is the total change in energy consumption; VOL is the change in energy consumption due to change in aggregate production, provided aggregate production is composed in the same way as at the initial point in time; COMP is the change in energy consumption due to change in the composition of aggregate production; INP is the change in energy consumption due to changed energy input coefficients; DIR is the change in energy consumption due to changed direct consumption of energy in the household sector.

This formula was used in conjunction with the results obtained in the base case simulation. The results are presented in Table 7.

TABLE 7 Decomposition of the total change in energy consumption, 1980–2000, in the base case.[a]

TOT	=	VOL	+	COMP	+	INP	+	DIR
9.2		5.1		1.4		−0.5		3.2

[a]Expressed in 10^9 SKr at 1968 prices.

Behind the positive figure denoted COMP in Table 7 are primarily two counteracting trends. One is that the production in "basic processing

* Thus $\bar{X}_i = [X_i(0)/X(0)]\,X(T)$ where $X(T) = \sum_{i=0}^{7} X_i(t)$.

industries" grows more slowly than aggregate production, which tends to reduce the energy intensity of GNP (see Table 4). This development is due to an absolute decline by 1.2% per annum of exports from this sector. In turn, this depends on an unfavorable development of domestic production costs in this sector in relation to world market prices. The other trend is the relatively rapid growth of the production of "housing services", which tends to increase the energy intensity of GNP.

Both these trends seem reasonable; but still there is reason to believe that the COMP figure in Table 7 is somewhat too low. This is because the structure of intersectoral deliveries, except for deliveries from the energy sector, is kept constant during the period 1980–2000. During the first postwar decades there was a trend towards more input of industrial goods per unit of output in the service sectors. A continuation of such a trend would increase the growth of production in "manufacturing industries" and as a result "basic processing industries", thus increasing the energy intensity of GNP. However, a *ceteris paribus* 10% increase of production in the latter sector in the year 2000 would only increase the COMP figure in Table 7 from 1.4 to 1.7.

The negative figure denoted INP in Table 7 reflects a reduction in energy input coefficients by less than 0.5 percentage points per annum. In comparison to the postwar experiences these figures seem fairly low. During the period 1950–1972 the industry's average energy input coefficient declined by 2.1% per annum in spite of an annual decrease of energy prices by 2.9% in real terms.* The figure denoted DIR reflects an annual growth at 3.6% of direct consumption in the household sector. Behind this figure are the relatively rapid growth of real private consumption and a comparatively high income elasticity for energy.

On balance, the base case consumption of energy per unit of GNP might represent an underestimation, but the opposite is also possible. If the base case figures are accepted, energy consumption in Sweden can be expected to grow more slowly for the rest of this century than during the first three postwar decades. That also holds in the case with "rapid growth" assumptions.

However, the "optimistic" GNP growth assumption in conjunction with such assumptions about technical change in the energy sector that the price of energy continues to decrease by 2.9% per annum leads to an annual GNP growth rate of 3.7% and an annual energy consumption growth rate of 4.7% in the model simulation. These figures are quite close to postwar averages. On the basis of these results it seems that the relatively

* In the base case simulation there was a slight increase in the price of energy.

small difference between the target energy consumption growth rate proposed by the government and the expected growth rate at "unchanged energy policy" and base case assumption primarily depends on the reduction in the growth of GNP together with slightly increasing energy prices. In any case, the difference between the target energy consumption growth rate proposed by the government and the growth rate obtained in the base case model simulation is only 1.8 percentage points per annum between 1980 and 2000, which is considerably less than expected when the 1975 government proposal was presented.

5.2 THE IMPACT OF A CONSTRAINT ON ENERGY CONSUMPTION

In this section it is assumed that a constraint is imposed on energy consumption. Thus, energy consumption is allowed to grow by 2% per annum between 1980 and 1985 and then remain constant. This policy is implemented by a value tax on all energy purchases. The tax revenues are assumed to be immediately distributed to the private sector. Thus, the energy tax only affects the relative market price of energy, while the size of the public sector is unaffected by the energy policy measures.*

TABLE 8 Calculated values of selected macroeconomic variables in the year 2000 under various assumptions about productivity growth and energy policy, 1980 = 100.

	Base case		Rapid growth case	
	No constraint on energy consumption	Constraint on energy consumption	No constraint on energy consumption	Constraint on energy consumption
GNP	148	147	202	196
Real household consumption	174	174	243	238
Energy consumption	163	110	231	110
Industrial employment	60	58	77	58

In Table 8 the main results, obtained in the "base" and the "rapid growth" cases with a constraint on energy consumption, are summarized.

* This implies that there are no direct costs for the implementation of the energy policy measures. In the real world a number of additional civil servants would probably have to be employed.

On the basis of the results presented in Table 8, energy policy of the kind discussed here seems to have a minor impact on the rate of economic growth. In the "base" case the effect corresponds to less than 1% of GNP in the year 2000, while the corresponding figure is 3% in the "rapid growth" case.

The impact of the energy policy can also be expressed in terms of the additions to the average working week which are necessary in order to fully compensate for the impact of the energy policy measures on GNP. In the "base" case, this figure is 3/4 hour per week and in the "rapid growth" case, 1 hour per week in the year 2000.

Obviously the economic impact of the energy policy measures depends to a large extent on the substitutability of energy and other factors of production. For this reason, the analysis of the base case is carried out for two additional sets of assumptions about the substitutability of energy and composite capital–labor. In one case the technology is said to be "rigid" in terms of energy input coefficients. Thus, the elasticity of substitution between energy and the composite capital–labor input is assumed to be 0.1 in all sectors. In the other case, where the technology is said to be "flexible", the corresponding figure is 0.5.

Given the other base case assumptions, including the assumption about no constraint on energy consumption, the rate and pattern of economic growth are practically the same in the "rigid" and the "flexible" cases as in the base case. This also applies to energy consumption.* Thus, the impact of the energy policy measured in the two cases can easily be compared.

In the "rigid" case the constraint on energy consumption reduces the rate of GNP growth by 0.1 percentage point per annum. This means that by the year 2000 the level of GNP is about 2% lower in comparison with a case without a constraint on energy consumption. In the "flexible" case the corresponding figure is lower than that of the "base" case.

These results are somewhat surprising. Even more surprising is perhaps that the energy consumption constraint has practically no impact on aggregate real consumption, either in the "rigid" or in the "flexible" case. This is because the slower growth of oil imports, resulting from the slower growth of energy consumption, leads to an improvement in the terms of trade.** Thus, the impact on the level of consumption by the

* The rate of economic growth is slightly more rapid in the "flexible" case than in the "rigid" case.

** World market oil prices are assumed to increase by 2% per annum between 1980 and 1990 and by 5% per annum between 1990 and 2000. The world market prices of other traded commodities are assumed to remain constant in real terms.

reduction in GNP is almost entirely offset by an increase of the share of consumption in GNP.*

Although the energy policy tends to reduce employment in industry, and in particular "basic processing industries", the results indicate that a constraint on energy consumption has a very small macroeconomic impact over a period of 20 years. However, the energy strategy has an impact on the economy, and the impact differs considerably between the "rigid" and the "flexible" cases. In Table 9 the difference in energy consumption is decomposed using formula (32). The results indicate that the nature of the adjustment mechanism depends to a large extent on the substitutability of energy and the composite capital–labor input.

TABLE 9 Percentage shares of the reduction in energy consumption by the year 2000, resulting from a constraint on energy consumption that can be assigned to various components under various assumptions about the substitutability of energy and composite capital–labor.

Elasticity of substitution	VOL	COMP	INP	DIR
0.10	24	6	32	39
0.25	13	6	57	23
0.50	2	5	79	13

In the "rigid" case the reduction of direct energy consumption in the household sector is the quantitatively most important part of the total change in energy consumption. Due to gradually increasing energy taxation the market price of energy grows by 10% per annum in this case. As a result, direct consumption of energy in the household sector grows by only 0.6% per annum as compared to 3.9% in the case without a constraint on total energy consumption. The energy input coefficients in the production sectors are not very much affected by the increasing market price of energy. They decline by less than 1% per annum in all sectors. As a result, reductions in energy input coefficients represent a fairly limited share of the total adjustment. Changes in the structure of the production system

* The same mechanism is at work in the "rapid growth" case. This can be shown in the following way. Real private consumption is about 50% of GNP. The development of aggregate net investment and public consumption are exogenously determined in the model. Thus, provided that the share of net exports in GNP is constant, the impact of the energy policy on private consumption should be about twice as big as the impact on GNP. As can be seen in Table 8, this is not the case. Consequently the energy policy tends to improve the terms of trade and thus increase the share of private consumption in GNP.

represent an even smaller share of the change in energy consumption. Nevertheless the energy policy leads to a more rapid reduction of industrial employment: − 3.0% per annum as compared to − 2.6% per annum in the case without constraint on total energy consumption.

In the "flexible" case energy input coefficients decline by 2.2–3.2% per annum. As a result, almost 80% of the change in energy consumption can be assigned to substitutions of the composite capital–labor input for energy in the production sectors. However, the decrease in energy input coefficients is accomplished primarily by means of input of more capital. This capital is available as a result of the reduced growth of the energy sector. One can say that capital is used for "energy conservation" rather than for energy production purposes.

In this case the growth of direct consumption of energy in the household sector is not affected by the energy policy to the same extent as in the "rigid" case. The annual growth rate is 2.8%, that is, the reduction due to the energy policy is slightly more than one percentage point per annum. Consequently only 13% of the total change in energy consumption can be assigned to changes in direct consumption of energy in the household sector.

In both the "rigid" and the "flexible" cases, higher energy taxes tend to reduce exports from "basic processing industries" and increase exports from "manufacturing industries". However, the resulting impact on the sectoral allocation of employment is not significant. The reason for this is that the reduced growth of the capital intensive energy sector leaves a larger share of net capital formation to be used as a substitute for energy in the production sectors. If the price elasticity of export demand is higher than assumed in the base case, domestic energy taxation tends to have a significant impact both on the structure of the production system and the sectoral allocation of the labor force. The results from a few experiments can be mentioned.

If the price elasticity of the demand for exports from the industrial sectors is assumed to be − 5 rather than − 3 and − 1.5, respectively, an annual increase of the energy tax rate with 10 percentage points would reduce the growth of production in "basic processing industries" by 0.4 percentage points. The corresponding figures for employment and exports would be 0.3 and 0.9, respectively. If the price elasticity figures are assumed to be − 10, the corresponding values become 1.9, 1.8 and 3.2.

According to the 1975 government proposal, the reason for imposing a constraint on energy consumption growth is the side effects associated with conventional fuels and electricity generation technologies. In the model simulations the target energy consumption growth rate was attained by means of a general value tax on energy purchases. The tax rate, which is endogenously determined in the model, indicates the marginal value in excess of production costs of one unit of energy. Thus the tax rate can be interpreted as a shadow price of "clean and safe energy", that is, the marginal willingness to pay for one unit of energy from a source without the side effects associated with conventional energy sources.

By the year 2000 the endogenously determined energy tax rate was 137% in the "flexible" case, 398% in the "base" case, and 871% in the "rigid" case. These results indicate the importance of the substitutability of energy and other factors of production. They also show that over a period of 20 years a constraint on energy consumption growth is likely to create substantial economic incentives for the development of energy sources without negative environmental and safety side effects.

So far the model results seem to indicate that attainment of the target growth rate for energy consumption proposed by the Swedish government would not have significant negative effects on conventionally measured economic growth. However, the picture becomes a little bit different if the impact is studied year by year rather than for the entire period 1980–2000. It then turns out that under the "base" case assumption the energy policy measures have practically no impact on GNP until the last five-year period. A similar pattern can be seen in the development of factor prices (Table 10).

TABLE 10 Reduction in the annual rates of change of wages and profits in the "base" case due to the constraint on total energy consumption percentage points.

	1980	1990	2000
Wage index[a]	−0.1	−0.4	−0.5
Profit index[b]	−0.3	−0.8	−1.2

[a]The variable W in the model.
[b]The variable R in the model.

Thus, for some time, energy consumption can be kept constant without significant reductions in the rate of economic growth. As time goes by, however, such a policy leads to a change in the economy's aggregate factor proportions; more capital is accumulated but it has to be combined with a constant amount of energy and, under the base case conditions, a slowly decreasing labor force. Accordingly, the "law of diminishing returns" comes into operation. Wages and, in particular, profits are negatively affected and the rate of economic growth is reduced.

In time, these effects become increasingly important, and more so the less flexible the technology is. However, over a 20-year period, the constraint on energy consumption does not seem to have significant effects on economic growth.

This conclusion is, however, subject to at least one important qualification. The reduction in the rate of profit due to the energy policy measures may not be compatible with the assumption about a constant net savings ratio. At least some additional policy measures may be needed in order to prevent a drop in total net investments. If it is assumed that such measures are not implemented and that the tendency towards reduced profits is offset by a drop in net investments, then the constraint on energy consumption leads to an additional reduction in economic growth. Under base case conditions such investment behavior leads to an additional reduction in GNP growth by, on the average, 0.3 percentage points per annum for 1980–2000. This means that the level of GNP in the year 2000 should be reduced by another 6 percentage points.

6 CONCLUSIONS

The purpose of this study has been to investigate to what extent there is a conflict in a small open economy between economic policy goals related to the growth of GNP or similar measures, and an energy policy aimed at zero growth in energy consumption. The analysis has focused on Sweden, a small economy with a relatively large foreign trade sector. In Sweden, energy policy presently aims at reducing the growth of energy consumption to 2% per annum up to 1985 and to zero growth thereafter provided such an energy policy is not in conflict with other social and economic goals. The analysis has been carried out by means of a numerically formulated model of the Swedish economy, and it has been focused on the period 1980–2000.

The results indicate that, for the 20-year period studied, the target energy consumption growth rate can be attained without significant costs in terms of GNP or aggregate household consumption losses. In addition, the energy policy did not lead to significant changes in the sectoral allocation of the labor force. This is because it was primarily capital available as a result of the reduced growth of the capital intensive energy sector that was used as a substitute for energy in the production sectors. However, the negative impact on economic growth increases with time. If the energy consumption is kept at the 1985 level during 5 or 10 additional years, the reduction in the rate of economic growth tends to be substantial.

The model simulations were carried out under the assumption that the net savings ratio in the economy remains constant over the period in question. Since one effect of the simulated policy measures was that profits tended to decrease, this assumption might seem dubious. The tendency towards falling profits might lead to a reduction in the net savings ratio, so that the proposed energy policy has an additional, indirect impact on economic growth. If, as an extreme example, the tendency of falling profits is completely balanced by reductions in total net investments, the previous conclusions have to be somewhat modified. Under base case assumptions, by the year 2000 the level of GNP is 7% lower in the case with a constraint on energy consumption. When capital formation was treated as an exogenous variable, the corresponding figure was 1%.

This case is extreme for two reasons. First, the energy policy measures can be combined with other measures for preventing the fall in profits. The existing tax system has a number of parameters which could be used for such purposes. Second, an important class of investment opportunities does not exist in the model economy: investments in R & D activities. This point, perhaps, needs some clarification.

In the model economy the target energy consumption growth rate was attained by means of a tax on energy consumption. By the year 2000 the tax rate, which kept energy consumption at the target level, varied between 137 and 871%, depending on the assumption made about the elasticity of substitution between energy and composite capital-labor. Energy tax rates of this order of magnitude obviously would create economic incentives for the development of new energy sources and energy conservation methods. It is quite possible that a number of R & D investments in these fields would turn out to have a high rate of return. Thus, by means of R & D investments the shape of the production functions would be changed so that the negative impact on economic growth of the energy policy would be mitigated and the tendency towards falling profits counteracted.

As expected, the proposed energy policy turned out to have a larger impact on economic growth where the elasticity of substitution between energy and composite capital-labor was low. In particular this applied on the sectoral level.

When the elasticity of substitution was assumed to be 0.50 in all sectors, neither the structure of the production system nor the commodity composition of household consumption was significantly affected. Thus, from a welfare point of view, GNP and aggregate household consumption have roughly the same meaning in the case with the energy policy measures as in the case without such measures.

However, when the elasticity of substitution was assumed to be 0.1, attainment of the target energy consumption development was accompanied by significant changes in the commodity composition of household consumption. In addition the rate of reduction of industrial employment was increased by the energy policy measures. This means that changes in aggregate measures such as GNP or aggregate household consumption become more difficult than usual to evaluate from a welfare point of view.

Obviously, the assumption about the substitutability of energy and other factors of production is an important one. On the basis of the econometric literature in this field it is difficult to say what would be the most realistic assumption in a study like this. However, the econometric results indicate that 0.10 is a rather "pessimistic" assumption, while 0.50 does not seem to be overly "optimistic".

Although reservations can be made, it seems that energy consumption in Sweden can be kept at the target development path proposed by the government at least during a period of 10–15 years without significant conflicts with other social and economic goals. Whether this is an "optimal", or justifiable, energy policy is another question, beyond the scope of this study.

It does not seem worthwhile to extend the analysis to the period after the year 2000. If the development of the model economy is simulated over a number of additional decades, with given technology and with the level of energy consumption kept at the 1985 level, it eventually collapses. But the technology cannot be regarded as given and constant over time. This is especially the case in a period where relative prices change substantially. R & D activities are likely to contribute to the development of new energy sources, new energy conservation methods and more flexible production techniques. In addition, they might lead to better methods of handling the side effects of existing energy sources, thereby removing the motive for an energy policy of the kind discussed in this study. This does not, of course, mean that everything will be fine a few decades into the next century. It only means that no conclusions about that period can be made on the basis of this study.

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APPENDIX

THE DERIVATION OF THE EQUATIONS OF THE LINEARIZED VERSION OF THE MODEL

Equations M1: 0–M1: 7

The relative rate of change of production can be written

$$x_i = \frac{\partial X_i}{\partial F_i}\frac{F_i}{X_i}f_i + \frac{\partial X_i}{\partial X_{0i}}\frac{X_{0i}}{X_i}x_{0i} \quad i = 0, 1, \ldots, 7 \qquad \text{(D1)}$$

Differentiation of eq. (1) with respect to F_i and X_{0i}, respectively, yields

$$\left.\begin{aligned} \frac{\partial X_i}{\partial F_i}\frac{F_i}{X_i} &= \gamma_i\left(\frac{A_iF_i}{X_i}\right)^{\rho_i} \\ \frac{\partial X_i}{\partial X_{0i}}\frac{X_{0i}}{X_i} &= (1-\gamma_i)\left(\frac{A_iX_{0i}}{X_i}\right)^{\rho_i} \end{aligned}\quad i = 0, 1, \ldots, 7 \right\} \qquad \text{(D2)}$$

Taking logs of eq. (2) and differentiating with respect to time yields

$$f_i = \alpha_i k_i + (1-\alpha_i)n_i + \lambda_i \quad i = 0, 1, \ldots, 7 \qquad \text{(D3)}$$

Using eqs. (10)–(12) and substituting (D2) and (D3) in (D1) yields

$$x_i = \frac{Q_iK_i}{P_i^*X_i}k_i + \frac{W_iN_i}{P_i^*X_i}n_i + \frac{W_iN_i + Q_iK_i}{P_i^*X_i}\lambda_i + \frac{T_iP_0X_{0i}}{P_i^*X_i}x_{0i} \quad i = 0, 1, \ldots, 7 \qquad \text{(D4)}$$

(D4) can then be written

$$x_i - \frac{\alpha_i}{1-\alpha_i}\frac{\omega_iWN_i}{P_i^*X_i}k_i - \frac{\omega_iWN_i}{P_i^*X_i}n_i - \frac{T_iP_0X_{0i}}{P_i^*X_i}x_{0i}$$
$$= \frac{1}{1-\alpha_i}\frac{\omega_iWN_i}{P_i^*X_i}\lambda_i \quad i = 0, 1, \ldots, 7 \qquad \text{(M1:}i\text{)}$$

Equation M2

This equation is obtained directly from eq. (28) by differentiation with respect to time.

Equations M3 and M4: i

Taking logs and differentiating eq. (10) with respect to time yields

$$p_i^* + (1-\rho_i)x_i + \rho_i f_i = w_i + n_i \quad i = 0, 1, \ldots, 7 \tag{D5}$$

Differentiation of eq. (6) with respect to time yields

$$\left.\begin{aligned} p_0^* &= \frac{1}{P_0^*}\left[P_0 p_0 - \sum_{j=1}^{5} P_j a_{j0} p_j - V\bar{P}_0 \bar{b}_0 (v + \bar{p}_0)\right] \\ P_i^* &= \frac{1}{P_i^*}\left[P_i p_i - \sum_{j=1}^{7} P_j a_{ji} p_j\right] \end{aligned}\right\} \tag{D6}$$

Next we define $A_{ji} = e_{ji} - a_{ji}$ where e_{ji} is 1 when $i = j$ for $j = 1, 2, \ldots, 7$, or 0 when $i \neq j$ for $i = 0, 1, \ldots, 7$.

Equation (D6) can then be written

$$\left.\begin{aligned} P_0^* &= \frac{P_0}{P_0^*} p_0 - \sum_{j=1}^{5} \frac{P_j a_{j0}}{P_0^*} p_j - \frac{V\bar{P}_0 \bar{b}_0}{P_0^*} v - \frac{V\bar{P}_0 \bar{b}_0}{P_0^*} \bar{p}_0 \\ p_i^* &= \sum_{j=1}^{7} \frac{P_j A_{ji}}{P_i^*} p_j \end{aligned}\right\} \tag{D7}$$

Equation (14) yields

$$w_i = w \quad i = 0, 1, \ldots, 7 \tag{D8}$$

Substitution of (D3), (D7) and (D8) in (D5) then yields

$$\frac{P_0}{P_0^*} p_0 - \sum_{j=1}^{7} \frac{P_j a_{j0}}{P_0^*} p_j - \frac{V\bar{P}_0 \bar{b}_0}{P_0^*} v + (1-\rho_0)x_0 + \rho_0 \alpha_0 k_0 + (\rho_0 - \alpha_0 \rho_0 - 1)n_0 - w = -\rho_0 \lambda_0 + \frac{V\bar{P}_0 \bar{b}_0}{P_0^*} \bar{p}_0 \tag{M3}$$

$$\sum_{j=1}^{7} \frac{P_i A_{ji}}{P_i^*} p_j + (1-\rho_i)x_i + \rho_i \alpha_i k_i + (\rho_i - \alpha_i \rho_i - 1)n_i - w = -p_i \lambda_i \quad i = 1, 2, \ldots, 7 \tag{M4: i}$$

Equation M5: i

Taking logs of eq. (11) and differentiating with respect to time yields

$$p_i^* + (1-\rho_i)x_i + \rho_i f_i = q_i + k_i \quad i = 0, 1, \ldots, 7 \tag{D9}$$

Substitution of eq. (13) in eq. (8) and differentiating with respect to time yields

$$q_i = \frac{P_8(\delta_i + \beta_i R)}{Q_i} p_8 + \frac{P_8 \beta_i R}{Q_i} r \quad i = 0, 1, \ldots, 7 \tag{D10}$$

Substitution of (D5), (D8) and (D10) in (D9) yields

$$\frac{P_8(\delta_i + \beta_i R)}{Q_i} p_8 + \frac{P_8 \beta_i R}{Q_i} r + k_i - w - n_i = 0 \quad i = 0, 1, \ldots, 7 \tag{M5:i}$$

Equations M6 and M7: i

Taking logs of eq. (12) and differentiating with respect to time yields

$$\left.\begin{aligned} p_0^* + (\rho_0 - 1)x_{00} - (\rho_0 - 1)x_0 &= p_0 \\ p_i^* + (\rho_i - 1)x_{0i} - (\rho_i - 1)x_i &= p_0 + t_i \quad i = 1, 2, \ldots, 7 \end{aligned}\right\} \tag{D11}$$

Differentiation of eq. (30) with respect to time gives

$$t_i = \frac{1}{T_i}(\dot{\tau} + \dot{\xi}_i) \quad i = 1, 2, \ldots, 7 \tag{D12}$$

Substitution of (D7) and (D12) in (D11) and rearrangement of terms yields

$$\begin{aligned} &\frac{P_0 - P_0^*}{P_0^*} p_0 - \sum_{j=1}^{7} \frac{P_j a_{j0}}{P_0^*} p_j - \frac{V\bar{P}_0 \bar{b}_0}{P_0^*} v \\ &+ (\rho_0 - 1)x_{00} - (\rho_0 - 1)x_0 = \frac{V\bar{P}_0 \bar{b}_0}{P_0^*} \bar{p}_0 \end{aligned} \tag{M6}$$

$$\begin{aligned} &\sum_{j=1}^{7} \frac{P_j A_{ji}}{P_i^*} p_j + (\rho_i - 1)x_{0i} - (\rho_i - 1)x_i - p_0 - \theta \frac{\dot{\tau}}{T_i} \\ &= (1-\theta)\frac{\dot{\tau}}{T_i} + \frac{\dot{\xi}_i}{T_i} \quad i = 1, 2, \ldots, 7 \end{aligned} \tag{M7:i}$$

where θ is either 1 or 0.

Equations M8–M17

These equations are obtained directly from eqs. (7), (15), (17), (18), (19), (4), (29), (25), (16) and (20), respectively, by differentiation with respect to time.

Equation M18

Differentiation of eq. (31) with respect to time yields eq. (18)

$$(1-\theta)Ee - X_0 x_0 - M_0 m_0 = -\theta Ee \qquad \text{(M18)}$$

where θ is either 1 or 0.

Equation M19

Differentiation of eq. (21) and using the definition of A_{ij} yields

$$\sum_{j=0}^{7} A_{ij} X_j x_j - C_i c_i - Z_i z_i + M_i m_i = 0 \quad i = 1, 2, \ldots, 5 \qquad \text{(M19)}$$

Equations M20–M24

These equations are obtained from eqs. (22), (23), (24), (27) and (26), respectively, by differentiation with respect to time.

THE ECONOMIC IMPACT MODEL

Yu. Kononov and A. Por

SUMMARY

The Energy Systems Program (ENP) of the International Institute for Applied Systems Analysis (IIASA) complements the efforts of other groups concerned with the question of how the world might move from an energy system based on oil and gas to one relying on essentially infinite, but highly capital intensive, energy resources. The ENP has been concerned with the identification and comparative evolution of strategies for this energy transition. The relevant modeling activity has been carried out under the project "Comparison of Energy Options, a Methodological Study," sponsored jointly by the United Nations Environment Programme (UNEP) and IIASA.

In this context, an initial version of the economic impact model (IMPACT) was developed at the Siberian Power Institute of the Siberian Branch of the USSR Academy of Sciences in Irkutsk. The model was originally designed to study the influence of the development of the energy sector on energy-related sectors of the national economy. Subsequently, the model was brought to IIASA where it was revised to focus on the identification, and comparison of long-term regional and global energy strategies in the transition period of 15 to 50 years from now. The possible influence of any given energy strategy on the economy is evaluated in terms of capital investment, manpower, materials, and natural resources that are needed to develop not only the energy supply system (ESS) but also the energy-related sectors of the economy.

This report describes IMPACT as it exists at IIASA, explains the computer program, and includes a user guide for implementing this methodology. It was stimulated by the interest in the model shown by a number of groups, among them the Bechtel Corporation in the U.S.; the Program Group for Systems Research and Technological Development at the Nuclear Research Installation in Juelich, Federal Republic of Germany; and the Bulgarian Ministry of Energy in Sofia.

1 INTRODUCTION

The energy supply system (ESS) is an essential component of an economy, although not a relatively large one. Attention has therefore been given recently to the study of the energy/economy interaction. The Energy Systems Program (ENP) at IIASA seeks, in its modeling work, to focus on this issue. The economic impact model (IMPACT) described in this report assesses the direct and the indirect requirements of alternative energy supply scenarios for capital investment, manpower, equipment, materials, and certain scarce resources. These data are used to evaluate the effects of the energy scenarios on the economy.

1.1 THE IIASA ENERGY SYSTEMS PROGRAM

A few words about the Energy Systems Program are in order. ENP focuses on the so-called *energy transition*: the slow, but major shift from the present energy system to a future sustainable one. The Program's considerations are primarily long term, spanning a horizon of 15 to 50 years from now – the period that IIASA believes encompasses the energy transition. The considerations are necessarily global: the present, large-scale supply and use of energy mandates an unprecedented degree of global interdependence. Global questions must be considered pivotal to all future energy studies.

A number of preliminary views and assumptions have helped to define IIASA's approach to the study of the energy problem.

– Energy systems are currently based on cheap oil and gas supplies; a gap between the world's expectations of such fuels and producers' ability or willingness to supply these amounts is expected in the late 1980s.

- As a result, there will almost certainly be continued increases in world energy prices; this new environment contrasts with that of the past energy scene during which energy prices were either constant or, in some cases, decreasing.
- Scientific and technological progress will contribute to a new capital intensiveness in energy systems that could have large feedback on economies. Large-scale energy investments are essential in the near and the long-term future.
- Concern for the environment will continue to influence global decisions in the energy arena.

The focus of the Energy Systems Program is the transition period – in particular the period of strategic investments beyond the year 2000. We hope to study that period by, in part, looking beyond it to the year 2030 or so, and then evaluating alternative paths through the transition. The computer modeling effort of the ENP is designed to implement, with some degree of comprehensiveness, this approach.

The goals of the IIASA energy modeling activity are fourfold:

- To study the long-term, dynamic (transitional), and strategic dimensions of regional and global energy systems
- To explore the embedding of such future energy systems and strategies into the economy, the environment, and society
- To develop a framework for assessing the global implications of long-term regional or national energy policies and, within this context, to evaluate methods for phasing the "best" energy strategies into various world regions
- To evaluate alternative strategies – to compare options – of a physical and technological kind, including their economic impacts

1.2 DIRECT AND INDIRECT REQUIREMENTS OF AN ENERGY SUPPLY STRATEGY

In the event of a rapid transition to the use of new, capital intensive energy resources, the total requirements – direct and the indirect – of a given energy supply strategy must be evaluated. The *direct requirements* are evaluated in terms of capital investment, manpower, materials, and equipment needed to construct and operate the energy facilities for implementing a national or a regional energy program. The *indirect requirements* refer to the resource and investment requirements of the energy-related sectors whose development is induced by the development of the ESS. In the event of such an energy transition, the additional investment in the machinery, metallurgy, construction, and other energy-related sectors could amount to 30 percent or more of the direct investment in the ESS. In this case, the indirect requirements for manpower and specific materials could exceed the direct input (Kononov and Makarov, 1975). Thus focusing only on the direct requirements can lead to serious underestimation and incomplete identification of possible constraints.

The simplest way of estimating the indirect influence of a given energy strategy on energy-related sectors is to apply a modified static input/output model: the direct material expenditures for constructing and operating the ESS could be represented as fixed final consumption. This approach was used by Bullard and Pilati (1975) of the University of Illinois for evaluating the construction requirements of the Project Independence scenario. However, this approach does not allow the estimation of the effect of the development of the ESS on the dynamics of capacities in energy-related sectors and on indirect capital investment. Accordingly, it does not take into account the relations and expenditures induced by capital investments in energy-related sectors.

Therefore, the above approach cannot give satisfactory results under conditions of rapid development of capital intensive energy resources and technologies. In this case a special model is needed.

1.3 DEVELOPMENT OF IMPACT

A dynamic, multisectoral model was constructed in 1972 at the Siberian Power Institute in Irkutsk, USSR; the model takes into account: (a) the construction lags – the gap in time between the start of investment and putting into operation of production capacities, and (b) the equipment and material consumption for each year of the construction period; it describes the intersectoral relations in both cost and physical terms. The model is convenient for computing and serves to investigate the influence of sizeable long-term changes in the technology, structure, and rates of energy development upon other, related branches of the national economy. Some characteristics of the Irkutsk model are given in Table 1 in the standard format of IIASA model surveys. A more detailed description can be found in Kononov (1976; 1972).

TABLE 1 Model of the external production relations of the energy supply system in the Soviet Union.

The model	Yu.D. Kononov, V.Z. Tkachenko, 1972 (Kononov, 1972; 1976). Siberian Power Institute, Irkutsk. Model of the external production relations of the energy supply system.
Subject and goal	• Relations of the energy system with metallurgy, engineering, construction industry, transport, and other sectors directly or indirectly contributing to its development by their products. • Approximate estimation of the influence of a changed pattern and development rate of energy production, and of changes in the technology of production or transportation of particular energy resources, on the development of related branches and on the national economy's total expenses (in terms of investment, labor and materials).
System described	The model covers all the main fuel deposits, groups of electric power stations and energy-production methods, and those industrial, transportation and construction sectors which largely depend for their progress on the development alternatives of energy production. The model takes into account that this dependence is complex and nonlinear and that some related branches have to be developed in advance of energy production. Extra demand for particular industrial products is assumed to be met either from expanded production capacities or from increased imports.
Area — Time	15 to 20 years ahead, described dynamically (in separate periods over the years considered).
Area — Space	The country as a whole.
Modeling techniques	The model belongs to the dynamic input–output models, explicitly accounting for lags between the start of investment and putting into operation of production capacities. It consists of linear and nonlinear equations, describing for each year of the period concerned: balances of the production of individual products and services and their consumption in operating and building the energy systems and related branches; and the conditions for introducing extra capacities in related branches. An iterative algorithm is used to resolve the model.
Input data	• Outputs of particular energy resources and commissioning of capacities in the energy system, specified by year; methods and ranges of energy transportation.

TABLE 1 *Continued.*

	• Import of individual industrial products for power production development • Export of individual industrial products compensating for hard-currency outlays for imported power resources. • Coefficients (rates) of material expenses for operation and construction in the energy system and related branches. • Standard time rates for building and putting into operation of individual production units. • Capital investment per unit of capacity increment in all the industries covered by the model. • Allocation of investment by year of building. • Labor-intensiveness of particular products and building projects.
Output data	Requisites for implementing the given development alternative of the energy system: • Outputs (direct and indirect expenses) of various industrial products, construction and transportation services. • Commissioning of capacities in related branches. • Priority of development of individual branches. • Direct and indirect (related) investment and manpower.
Observations	The model serves as a tool to study the effects produced by major and prolonged changes in ESS development on other economic branches (it consists of some 50 sectors and industries). It is also of help in long-range planning and forecasting for estimating the constraints imposed on ESS development by related branches; investigating the uncertainty zone of this development; and tentatively assessing the set of measures and the dates for implementing particular energy alternatives.

SOURCE: Beaujean and Charpentier (1976, p.2).

At IIASA, the Irkutsk model was developed further and adjusted to purposes of identification and comparison of long-range regional energy strategies in the transition period. This modified version of the model, called the economic impact model (IMPACT), differs from the analogue Irkutsk model in the following ways:

- The time horizon has been extended in IMPACT to include the period 15 to 50 years from now.
- IMPACT has been generalized to include new energy technologies (e.g., fast breeder reactors, coal gasification and liquefaction, solar and geothermal energy, hydrogen production).

- The composition and the number of energy-related sectors have been revised in IMPACT.
- The additional production of export goods, compensating for hard currency outlays for imported fuel, has been taken into account in IMPACT.
- IMPACT evaluates the direct and the indirect WELMM (Water, Energy, Land, Materials, and Manpower) expenditures and potential environmental impacts.
- The computer program of IMPACT has been improved.

1.4 MODEL ASSUMPTIONS

IMPACT gives the range of total (direct and indirect) expenditures. For the minimum range, it has been assumed that the ESS can be developed without putting into operation the production capacities of the energy-related sectors; enterprises producing equipment related to energy supply and use – such as turbogenerators, reactors, and mining equipment – are the exception. For the maximum values of total expenditures, there are no limitations on putting into operation the capacities of the energy-related sectors, and the requirements for the additional development of the machinery, metallurgy, and chemical industries as well as for other related branches of the national economy have been considered.

IMPACT assumes that capacity in the first year of each scenario is adequate for the level of energy output. (For the long-run scenarios used at IIASA, capacity for the first 5 years or so is nearly the same for all scenarios.)

IMPACT also assumes that imports of capital equipment are given exogenously. Thus in a region where most of the capital equipment is locally produced, the scenario should calculate a minimum amount of imports. However, in a region where there is large-scale importing of technically advanced energy equipment, the scenario should specify the equipment as imports so that investment in domestic industries to produce such equipment will not be generated by the model.

1.5 MODEL SCOPE

Explicitly, IMPACT can answer the following questions:

- What direct capital investment would be needed to implement a given energy strategy? When?

– What direct expenses of materials, equipment, manpower, and scarce natural resources would be required to construct and operate new energy facilities? When?

Roughly, IMPACT can address the following questions:

– What production capacities in energy-related sectors would be required to implement a given energy strategy? When?
– What indirect capital, manpower, materials, and scarce natural resources would be needed to implement a given energy strategy? When?
– How different are the total (direct and indirect) requirements of different energy strategies for limited national and natural resources?
– What are the potential direct and indirect environmental impacts of a given energy strategy?

IMPACT can be helpful in answering the following questions:

– How will the transition to essentially infinite, but highly capital intensive, energy resources affect macroeconomic indices?
– What capital, manpower, and material resource categories are potential bottlenecks to implementing a given energy strategy?
– Is a given energy strategy feasible? If not, what can be done to make it feasible?

At this point we should state what IMPACT can *not* do. IMPACT does not calculate price changes resulting from various scenarios, and does not assess the effects of such changes on final demand or on intermediate demand. Moreover, IMPACT does not check the capacity requirements of energy-related sectors in the first year against existing stocks. Such checking is not possible since IMPACT is not a model of the whole economy. For example, it would be meaningless to compare cement production generated by IMPACT with cement capacity, because the production estimates by IMPACT do not include the use for residential or highway construction.

1.6 LINKAGE OF IMPACT WITH OTHER ENERGY MODELS

IMPACT is an integral part of the IIASA set of energy models which has been designed for studying the long-term, dynamic, and regional and global aspects of large-scale energy systems (Figure 1). The critical question concerned in the modeling is whether economies can afford the requisite expenditures of time and capital to achieve alternative energy strategies during the long-term transition to sustainable energy systems. The several individual models and their interrelationships were developed with these considerations in mind. The design and application of the IIASA set of energy models is discussed by Paul Basile, Assistant Leader of the ENP, in a report that is in preparation.

IMPACT provides the evaluation of the requirements of a given energy strategy in terms of capital investment, manpower, and other scarce resources. This output is then used to assess the possible impact of the strategy on some macroeconomic indices.

At IIASA, for example, a one-sector macroeconomic model (MACRO) has been developed in order to evaluate the possible dynamics

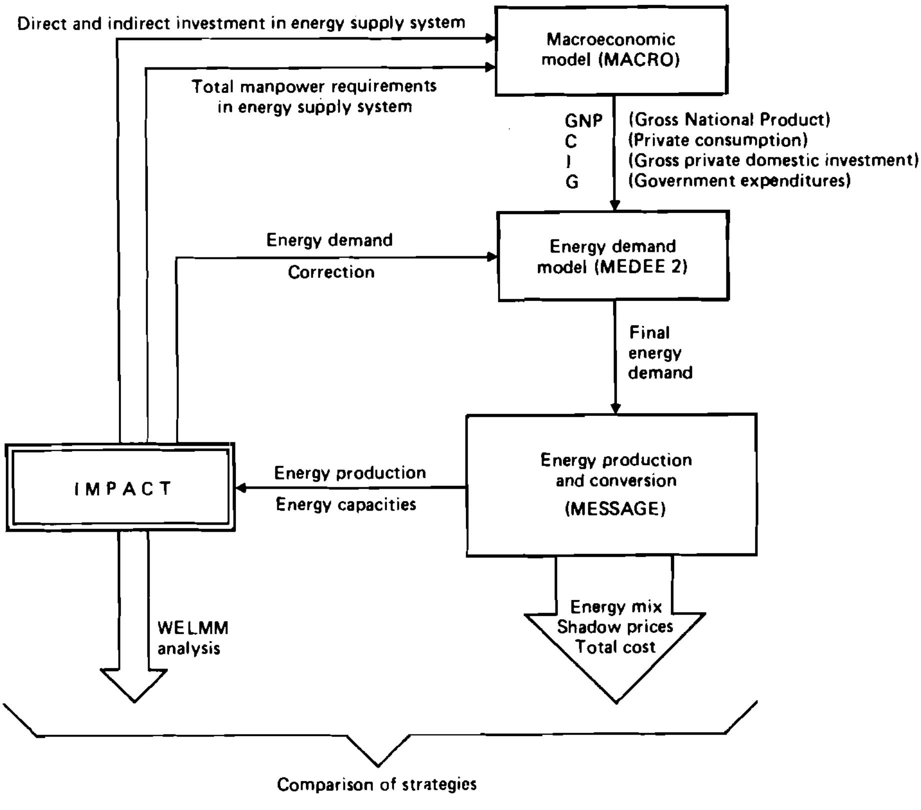

FIGURE 1 Linkage of IMPACT with other IIASA energy models.

of gross national product (GNP), private consumption, gross private domestic investment, and government expenditure (Rogner, 1977). By linking IMPACT with MACRO (Figure 1), it is possible to:

- Compare the designed share of energy in gross private domestic investment and employment with historical data, and thereby assess the possible difficulties of providing a given energy strategy with capital investment and manpower
- Correct corresponding variables of MACRO and evaluate roughly the possible impact of a given energy strategy on GNP and private consumption growth rates

Theoretically, by using a *multisectoral* macroeconomic model, the accuracy and completeness of the economic impact evaluation would be increased.

IMPACT is unique as a model for evaluating the energy/economy linkage in this manner. One of the few exceptions is the Energy Supply Planning Model (Carasco *et al.*, 1975), developed by the Bechtel Corporation in the U.S. Bechtel's model determines the *direct* requirements for capital, manpower, materials, and equipment associated with the construction and operation of energy facilities required to implement a given national or regional energy program, but it does not take into account the *indirect* requirements. IMPACT can be used in conjunction with the Bechtel Energy Supply Planning Model: the input data for IMPACT are the direct requirements of the ESS for materials and equipment, which represent output from the Bechtel model.

2 GENERAL DESCRIPTION OF IMPACT

The inputs to IMPACT are the time paths of energy production by type of energy and by method of production. This input can be provided by an energy supply model – for instance, the IIASA MESSAGE model. If needed, IMPACT, employing the user's specification, can disaggregate a given strategy and evaluate requirements for new capacities for transportation and conversion of energy resources.

2.1 MODULES

The model is divided into five modules (Figure 2).

The *first module* calculates the direct material and equipment requirements ($Y_e(t)$) for the construction and operation of energy facilities for implementing a given energy supply strategy. The ESS is represented in the prototype model by 58 energy activities; Table 2 groups these activities according to the energy source. A list of the energy activities included in IMPACT is given in Appendix A.

The first module may be omitted if IMPACT works in conjunction with the Bechtel Energy Supply Planning Model. In this case, the input data for IMPACT are the direct material and equipment requirements of the ESS, which represent output from the Bechtel model.

The *second module*, using an I/O technique, describes the relationship between the ESS and the energy-related sectors. The module calculates the required production output in the energy-related sectors needed to support energy development ($X_1(t)$). The prototype model includes 36 sectors and types of industrial products (see Appendix A). For these sectors the following assumptions were made:

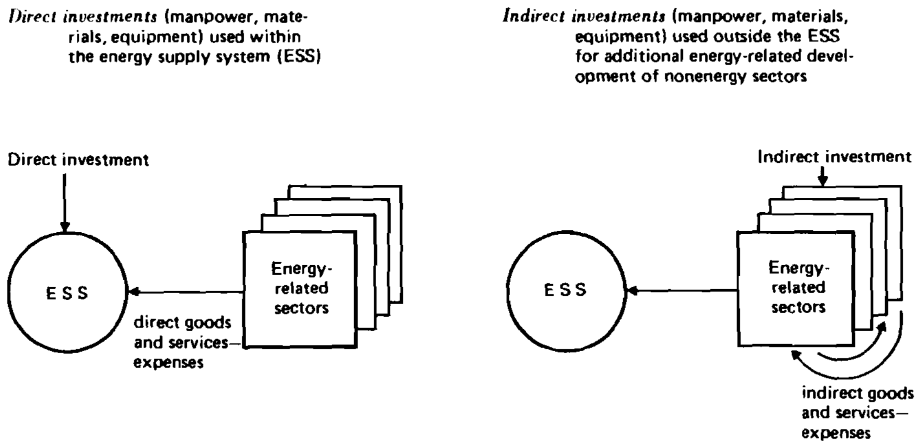

FIGURE 2 Definition of terms for IMPACT.

- Products are manufactured by a single method – that is, there is no choice of technology or distribution. Where known, the most progressive production methods are assumed.
- The coefficients of material, capital, and manpower inputs per unit of production or capacity expansion do not depend on the scale of production.

TABLE 2 Energy activities in IMPACT.

Energy source	Number of activities
Oil and oil shale extraction and refining	7
Gas extraction	4
Coal mining	3
Synthetic fuels from coal	4
Hydrogen production	3
Fuels, transportation, storage, and distribution	12
Conventional power plants	4
Nuclear power plants	3
Nuclear fuel cycle	9
Geothermal power complex	1
Solar power plants	1
Electricity transmission and distribution	1
Miscellaneous	6

The *third module* determines capacity expansion requirements of energy-related sectors ($Z_1(t)$). The additional capacity required by the end of year t is the difference between estimated output in year $t+1$ and actual production in the previous peak year.

The *fourth module* estimates the capital investment required for the capacity expansion determined in module 3. Capital investment in any year depends upon capacity expansion in the current and future years and on replacement requirements. The feedback between modules 4 and 2 is achieved in IMPACT by means of an iterative procedure, which is described later in this report. In a mathematical sense, modules 2, 3, and 4 represent an indivisible system of equations.

The *fifth module* estimates the WELMM requirements of the ESS and evaluates the effects of water and air pollution on the system.

3 MATHEMATICAL DESCRIPTION OF IMPACT

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

3.1 THE EQUATION SYSTEM OF IMPACT

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

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

where

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

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

$\overline{Z}_e(t)$ is the vector of required additional capacities of the ESS in the year t

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

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

$\hat{\tau}$ is the lead time (construction lag)

Total (direct and indirect) material and equipment requirements of the ESS are expressed as

$$X_1(t) = A_2X_1(t) + A_3X_2^{in}(t) + Y_e(t) \tag{2}$$

where

A_2 is the matrix of input/output coefficients
A_3 is the matrix of materials and equipment requirements coefficients per unit of investment in energy-related sectors
$X_1(t)$ is the vector of output in energy-related sectors
$X_2^{in}(t)$ is the vector of indirect capital investments in energy-related sectors

Direct capital investment in the ESS is expressed as

$$X_2^d(t) = \sum_{\tau=t}^{t+\hat{\tau}} F_2^{(\tau-t)}\overline{Z}_e(\tau)$$

Indirect capital investment in the ESS is expressed as

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

Total (direct and indirect) capital investment in the ESS is expressed as

$$X_2^{(t)} = X_2^d(t) + X_2^{in}(t) \tag{3}$$

where

$F_2^{(\tau-t)}$, $F_3^{(\tau-t)}$ are, respectively, the matrices of capital investment coefficients in the year t to put into operation the additional capacities of the ESS and energy-related sectors in the year τ
$Z_1(t)$ is the vector of new additional capacities in the energy-related sectors in the year t
$X_2^d(t)$ is the vector of direct capital investment in the ESS

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

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

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

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

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

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

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

$$Z_1(t) = \max \left[\min_{\tau \leqslant t} \left(X_1(t+1) - X_1(\tau) \right); 0 \right] \tag{4}$$

The structure of IMPACT is shown in Figure 3.

3.2 AUXILIARY EQUATIONS OF IMPACT

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

$$X_3(t) = A_4 \overline{X}_e(t) + A_5 X_1(t) + A_6 X_2^{in}(t) + \sum_{\tau = t}^{t+\hat{\tau}} F_4^{(\tau - t)} \overline{Z}_e(\tau) \tag{5}$$

where

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

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

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

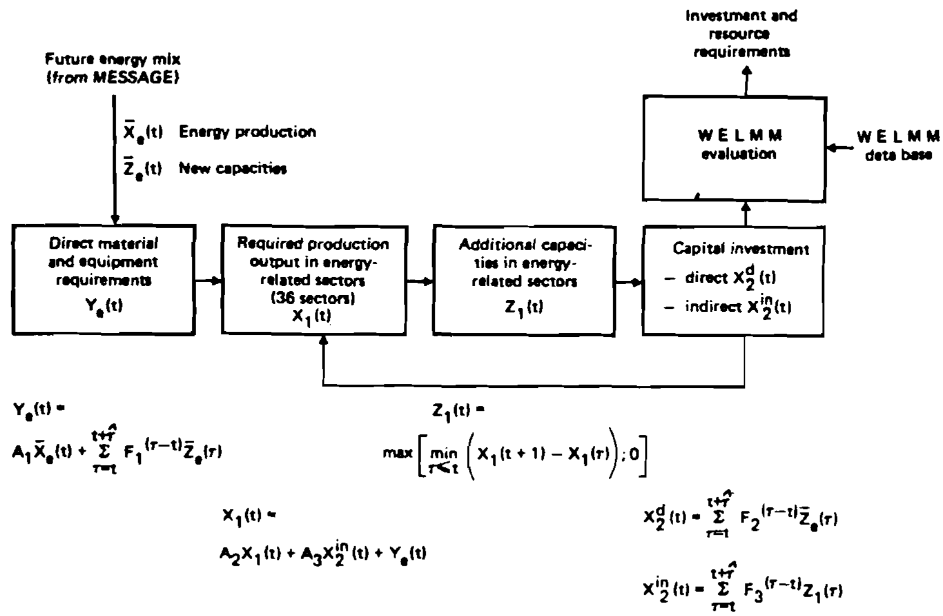

FIGURE 3 Structure of IMPACT.

3.3 THE ALGORITHM

Symbol A is used to denote the matrix composed of matrices $A_1, A_2, \ldots, A_6$ as follows:

$$A = \begin{bmatrix} A_1 & A_2 & A_3 \\ 0 & 0 & 0 \\ A_4 & A_5 & A_6 \end{bmatrix}$$

The zero matrices contain as many rows as the number of columns in matrix A_3.

Similarly, symbol $F^{(\tau-t)}$ is used to denote the matrix composed of matrices $F_1^{(\tau-t)}, \ldots, F_4^{(\tau-t)}$ as follows:

$$F^{(\tau-t)} = \begin{bmatrix} F_1^{(\tau-t)} & 0 & 0 \\ F_2^{(\tau-t)} & F_3^{(\tau-t)} & 0 \\ F_4^{(\tau-t)} & 0 & 0 \end{bmatrix}$$

The zero matrices in the third column contain as many columns as the number of columns in matrix A_3.

The detailed structures of matrices A and $F^{(\tau-t)}$ $(t \leqslant \tau \leqslant t+\hat{\tau})$ are given in Figures 4 and 5. By means of these new matrix symbols the model can be written in the following reduced form:

$$X^*(t) = AX(t) + \sum_{\tau=t}^{t+\hat{\tau}} F^{(\tau-t)} Z(\tau)$$

$$Z_1(t) = \max \left[\min_{\tau \leqslant t} (X_1(t+1) - X_1(\tau)); 0 \right] \qquad (6)$$

where

$$X^*(t) = (X_1(t), X_2(t), X_3(t))$$
$$X(t) = (\overline{X}_e(t), X_1(t), X_2{}^{in}(t))$$
$$Z(t) = (\overline{Z}_e(t), Z_1(t), 0)$$

This form of the model is important because the data for the computer program must be prepared as A and $F^{(0)}, \ldots, F^{(\hat{\tau})}$ matrices.

Since $\overline{X}_e(t)$ and $\overline{Z}_e(t)$ are exogenous variables, and vector $X_3(t)$ depends on vectors $X_1(t)$ and $X_2(t)$ (but does not influence them), the model may be written in the following reduced form:

$$X(t) = AX(t) + \sum_{\tau=t}^{t+\hat{\tau}} F^{(\tau-t)} Z(\tau) + Y(t) \qquad (7)$$

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

where

$$X(t) = (X_1(t), X_2{}^{in}(t))$$
$$Z(t) = (Z_1(t), 0)$$
$$Y(t) = (Y_e(t), 0)$$
$$A = \begin{bmatrix} A_2 & A_3 \\ 0 & 0 \end{bmatrix}$$
$$F^{(\tau-t)} = \begin{bmatrix} 0 & 0 \\ F_3{}^{(\tau-t)} & 0 \end{bmatrix}$$

for every τ such that $t \leqslant \tau \leqslant t + \hat{\tau}$.

In order to solve this dynamic equation system (with lag $\hat{\tau}$), a set of initial conditions has been defined which specify $\hat{\tau}$ consecutive values of $X(t)$ and $Z(t)$.

	Energy supply system	Energy-related sectors	Capital investment	Vector $X^*(t)$
Energy-related sectors	A_1	A_2	A_3	$X_1(t)$
Capital investment	0	0	0	$X_2(t)$
WELMM	A_4	A_5	A_6	$X_3(t)$
Vector $X(t)$	$\bar{X}_e(t)$	$X_1(t)$	$X_2^{in}(t)$	

FIGURE 4 Structure of matrix A and of vectors $X^*(t)$ and $X(t)$.

	Energy supply system	Energy-related sectors	Capital investment
Energy-related sectors	F_1	0	0
Capital investment	F_2	F_3	0
WELMM	F_4	0	0
Vector $Z(t)$	$\bar{Z}_e(t)$	$Z_1(t)$	0

FIGURE 5 Structure of matrices $F^{(0)}, \ldots, F^{(\hat{\tau})}$ and of vector $Z(t)$.

The model calculates the economic impact of a given energy strategy for a given time interval (from t_0 to T); it does not take into account investment requirements for putting into operation new additional energy capacities after the year T. That is,

$$Z(t) = 0 \quad \text{if } t \geqslant T$$

$$X(t) = 0 \quad \text{if } t \geqslant T + 1$$

Thus, the model seeks to find all values of $X(t)$ for t less than $T + 1$ and for t greater than $t_0 - 1$. With these conditions, the model has the following format:

$$\begin{aligned}
X(T) &= AX(T) + Y(T) \\
X(T-1) &= AX(T-1) + F^{(0)}Z(T-1) + Y(T-1) \\
X(T-2) &= AX(T-2) + F^{(0)}Z(T-2) + F^{(1)}Z(T-1) + Y(T-2) \qquad (8) \\
&\vdots \\
X(t) &= AX(t) + F^{(0)}Z(t) + F^{(1)}Z(t+1) + \ldots + F^{(\hat{\tau})}Z(t_0 + \hat{\tau}) + Y(t_0) \\
&\vdots \\
X(t_0) &= AX(t_0) + F^{(0)}Z(t_0) + F^{(1)}Z(t_0 + 1) + \ldots + F^{(\hat{\tau})}Z(t_0 + \hat{\tau}) \\
&\quad + Y(t_0) \\
Z(T-1) &= \max \left[\min_{t_0 \leqslant \tau < T} (X(T) - X(\tau)); 0 \right] \\
Z(T-2) &= \max \left[\min_{t_0 \leqslant \tau < T-1} (X(T-1) - X(\tau)); 0 \right] \\
&\vdots \\
Z(t_0) &= \max \left[(X(t_0 + 1) - X(t_0); 0 \right]
\end{aligned}$$

An iterative method – a modification of the Gauss–Seidel procedures – has been used to solve the equation system. The program proceeds from an initial "guess", the elements of which are set to zero. The program then defines a sequence of approximations which, in principle, converge to the solution.

Briefly, the algorithm is as follows: the Gauss–Seidel iteration procedure is used to solve the first subsystem

$$X(T) = AX(T) + Y(T)$$

Clearly the solution $X(T)$ to this subsystem does not depend on the other variables of system (8). The kth cycle of the iterative algorithm for solving the remaining part of equation system (8) constitutes one execution of the following two-step procedure.

Step 1. The Gauss–Seidel procedure is used to solve the equation system

$$X(T-1) = AX(T-1) + F^{(0)}Z(T-1) + Y(T-1)$$
$$\vdots$$
$$X(t_0) = AX(t_0) + F^{(0)}Z(t_0) + F^{(1)}Z(t_0+1) + \ldots + F^{(\hat{\tau})}Z(t_0+\hat{\tau}) + Y(1)$$

Vectors $Z(t)$, $(t = t_0, \ldots, T-1)$ are considered given from the $k-1$ cycle.

Step 2. Compute the values of vectors $Z(t)$ $(t = t_0, \ldots, T-1)$ by using the components of vectors $X(t)$ $(t = 1, 2, \ldots, T)$, obtained from step 1, and return to step 1.

A necessary condition for the convergence of this procedure is that matrix A be a so-called *convergent matrix*, i.e. that $\lim_{n\to\infty} A^m = 0$. Matrix A is convergent if all eigenvalues of A are less than 1 in absolute value; in that case, matrix I–A is nonsingular, where matrix I denotes the identity matrix. Step 2 of the iterative algorithm is concerned primarily with solving linear-equation systems of the type $X = AX + b$ where matrix A is the same for every time period $(t = 1, \ldots, T-1)$ and only vector b differs.

Although from the computational point of view it would seem more efficient to determine in advance the inverse of matrix I–A and to use this for solving the equation system, the authors have not done so because the inversion procedure would increase the core requirements of the program by a factor of 2.

From the economical point of view, it is convenient to provide data for matrices $F^{(0)}, \ldots, F^{(\hat{\tau})}$ in the form of matrices $C, S_0, \ldots, S_{\hat{\tau}}$, where C is the matrix of expenditures coefficients for energy equipment per unit of capacity, and matrices $S_0, \ldots, S_{\hat{\tau}}$ are the coefficients of capital investment, material, and equipment distribution for each year of the construction period. The elements of matrices $F^{(0)}, \ldots, F^{(\hat{\tau})}$ are computed by multiplying the corresponding elements of matrices $C, S_0, \ldots, S_{\hat{\tau}}$.

4 DESCRIPTION OF THE COMPUTER PROGRAM

4.1 GENERAL CHARACTERISTICS

IMPACT was programmed in Fortran. Two versions of the model are available: the first version for use on the IBM 370; and the second one for use on the PDP 11/70 computer, which is operating at IIASA. For each of the versions there are three executable programs:

- IMDATA (input conversion and data modification)
- IMSETUP (model setup)
- IMSOLVE (solution algorithm)

The components of the IMPACT model system are shown in Figure 6.

All three programs run standalone under UNIX within the 56K word limit of the PDP 11/70. There are almost no limits on the model size of the PDP 11/70 because the core used for data storage depends only linearly on the size of the coefficient matrices.

IMPACT runs on the IBM 370 for the VM/370-CMS environment. Since the model operates almost entirely in-core, model size had to be limited to a maximum of 156 rows and 156 columns for matrices A, F^0, ..., $F^{(\hat{\tau})}$. Although the IBM 370 is less convenient than the PDP 11/70, the speed of execution of the IBM 370 is greater: a factor of some 30 exists between the time required to solve a problem on the IBM 370 as compared with the PDP 11/70, with a running time of 3 to 7 minutes on the IBM 370.

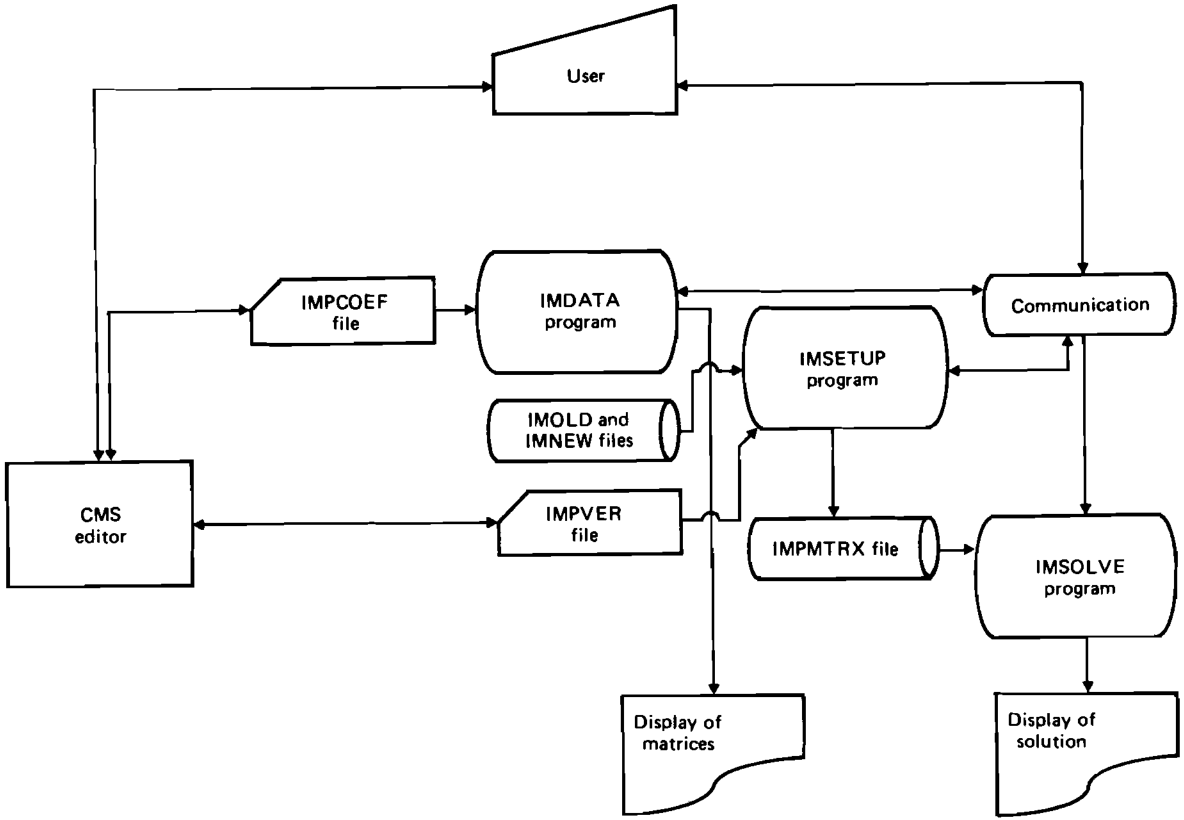

FIGURE 6 Components of the IMPACT model system.

4.2 THE IMPACT PROGRAM SYSTEM

4.2.1 Program IMDATA

Program IMDATA, which is the first component of the interactive IMPACT system for the VM/370-CMS environment, is designed to create and maintain data file IMOLD containing the coefficients of matrices A, C, $S_0, \ldots, S_{\hat{\tau}}$, where

- A is the matrix composed of matrices $A_1, A_2, \ldots, A_6$
- C is the matrix of expenditure coefficients for energy equipment per unit of capacity
- S_τ is the matrix of capital investment, material, and equipment distribution coefficients for each year τ of the construction period $0 \leqslant \tau \leqslant \hat{\tau}$

The sequence of operations executed in a program run is controlled by the user through interactive control commands and control variables. The procedures that can be initiated by the control commands are:

- INPUT (reads matrix data cards)
- MODIFY (reads correction data for modifying the matrices)
- LIST (displays the model matrices A, C, $S_0, \ldots, S_{\hat{\tau}}$ in various formats)

INPUT specifies matrix A and matrices C, $S_0, \ldots, S_{\hat{\tau}}$. INPUT reads the input data from file IMPCOEF, converts them into compact internal representation, and stores the converted data in file IMOLD. Only one IMOLD file can exist at a time; previously created IMOLD files must be renamed for future use before the current invocation of IMDATA. (For the organization of the file IMPCOEF and for the setup of the data deck for the INPUT procedure, see Section 5.1.2.)

The MODIFY procedure updates elements of matrices A, C, $S_0, \ldots, S_{\hat{\tau}}$ according to the input data given in file IMPCOEF. Corrections to elements of matrices A, C, $S_0, \ldots, S_{\hat{\tau}}$ are contained in file IMPCOEF. The setup of the data deck for the MODIFY procedure is given in Section 5.1.2. The MODIFY procedure uses data file IMOLD as the input file, and the updated file is written either back to the file IMOLD or to a new file IMNEW.

The LIST procedure displays on the standard printing device the entire matrices or selected parts thereof.

The control commands and the control variables for program IMDATA are discussed in Section 5.1.1.

Program IMDATA consists of one main program with seven subroutines; the subroutines are as follows:

Model input and modify level

INPUT (controls input and modifying level)
CUTA (inputs or modifies matrix A)
CUTF (inputs or modifies matrices C, $S_0, \ldots, S_{\hat{\tau}}$)
SUB (updates or creates model coefficients of file IMOLD)

Model output level

PRINT (controls printing matrices)
BER (prepares submatrices for printing)
LIST (displays submatrices in tabular form)

Figure 7 is a flow chart of the major subroutines and data files of program IMDATA.

4.2.1.1 MAIN PROGRAM

The main program opens input file IMPCOEF and data file IMOLD and calls subroutines INPUT and PRINT. Both the input and the output levels are controlled interactively. Program IMDATA has its own simple command language, consisting of seven control commands and eight control variables. A description of the control commands and control variables is given in Section 5.1.1.

4.2.1.2 SUBROUTINE INPUT

Subroutine INPUT manages the input and modify level. After all necessary parameter variables have been entered (see Section 5.1.1), the program reads file IMPCOEF. Subroutine PRODN reads product names; subroutines CUTA and CUTF read, respectively, A-MATRIX and F-MATRIX data cards. After the EOJ (end of data deck) card has been encountered, the program calls subroutine SUB to either update file IMOLD, if it exists, or create a new file, IMNEW.

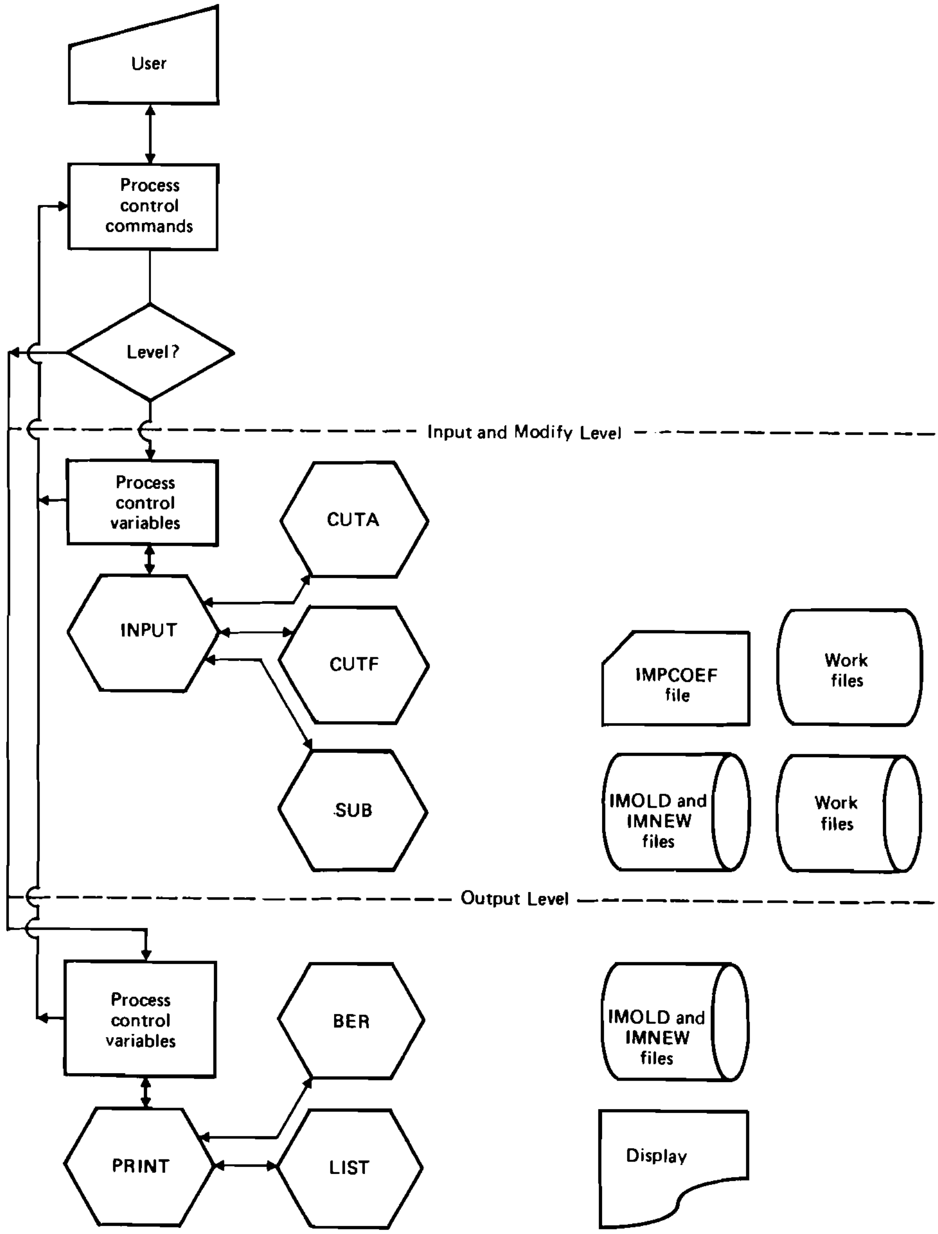

FIGURE 7 Program IMDATA.

4.2.1.3 SUBROUTINE PRINT

Subroutine PRINT manages the output level. After values of the control variables giving the name of the matrix and the index of the submatrix to be printed have been prompted, subroutine BER is called to prepare the submatrix for printing. The chosen submatrix is then displayed by subroutine LIST.

4.2.2 Program IMSETUP

Program IMSETUP, which is the second component of the interactive IMPACT system for the VM/370-CMS environment, is used to set up IMPACT for solution. Program IMSETUP creates the output file IMPMTRX from matrices A, $F^{(0)}$, ..., $F^{(\hat{\tau})}$, from the exogenous values for annual energy production ($\overline{X}_e$) and for additional capacities in the ESS ($\overline{Z}_e$), and from the model parameters, starting year (t_0), finishing year (T), and number of $F^{(\tau)}$ matrices, i.e., lag value $\hat{\tau}$ plus 1. The elements of matrix $F^{(\hat{\tau})}$ are computed by multiplying the corresponding elements of matrices C and $S_{\hat{\tau}}$.

Program IMSETUP uses as input the data file IMOLD (maintained by program IMDATA) and data file IMPVER which contains the exogenous variables $\overline{X}_e$ and $\overline{Z}_e$. Annual energy production ($\overline{X}_e$) is given for every nth year; program IMSETUP interpolates linearly the value for the other years. Additional capacities in the ESS ($\overline{Z}_e$) are given as the sum of capacity values for n consecutive years. A prescribed distribution function distributes these values over the other years. The format of file IMPVER, which should be prepared by the user, is given in Section 5.2.2.

The output of program IMSETUP is file IMPMTRX. Only one IMPMTRX file can exist at a time; previously created IMPMTRX files should be renamed. Execution time for IMSETUP is short.

Program IMSETUP consists of one main program with five subroutines; the subroutines are as follows:

Model coefficient setup level

SUB (controls setup level)
ACONV (sets up coefficients of matrix A)
FCONV (sets up coefficients of matrices $F^{(0)}, \ldots, F^{(\hat{\tau})}$)
SZET (auxiliary subroutine for subroutine FCONV)

Exogenous vector setup level

INTERP (interpolates annual values for vectors $\overline{X}_e(t)$ and $\overline{Z}_e(t)$)

Figure 8 is a flow chart of the major subroutines and files of program IMSETUP.

4.2.2.1 MAIN PROGRAM

The main program opens data files IMOLD and IMPVER, initializes the parameters, and calls subroutines ACONV, FCONV, and INTERP in order to set up file IMPMTRX. The setup is controlled interactively. Program IMSETUP has its own simple command language, consisting of about three control commands and six control variables. A description of the control commands and control variables is given in Section 5.2.1.

4.2.2.2 SUBROUTINE ACONV

Program IMSOLVE uses matrix A in the same format as it is stored in data file IMOLD; thus, the program's setup requires only slight modification to the storage format and its copying from the data base to file IMPMTRX. Changes in the coefficients of matrix A can be made by using the interactive command CHANGE. These modifications can be made only in file IMPMTRX.

4.2.2.3 SUBROUTINE FCONV

Subroutine FCONV computes the elements of matrices $F^{(0)}, \ldots, F^{(\hat{\tau})}$. The user submits the data for matrices $F^{(0)}$ in the form of matrices $C, S_0, \ldots, S_{\hat{\tau}}$, where C represents the matrix of expenditures for energy equipment per unit of capacity, and matrices $S_0, \ldots, S_{\hat{\tau}}$ represent the coefficients of capital investment, material, and equipment distribution for each year of the construction period. The elements of matrices $F^{(0)}$ are computed by multiplying the corresponding elements of matrices $C, S_0, \ldots, S_{\hat{\tau}}$. Temporary changes in the elements of matrices $C, S_0, \ldots, S_{\hat{\tau}}$ can be made interactively by using the control command CHANGE. These modifications can be made only in file IMPMTRX.

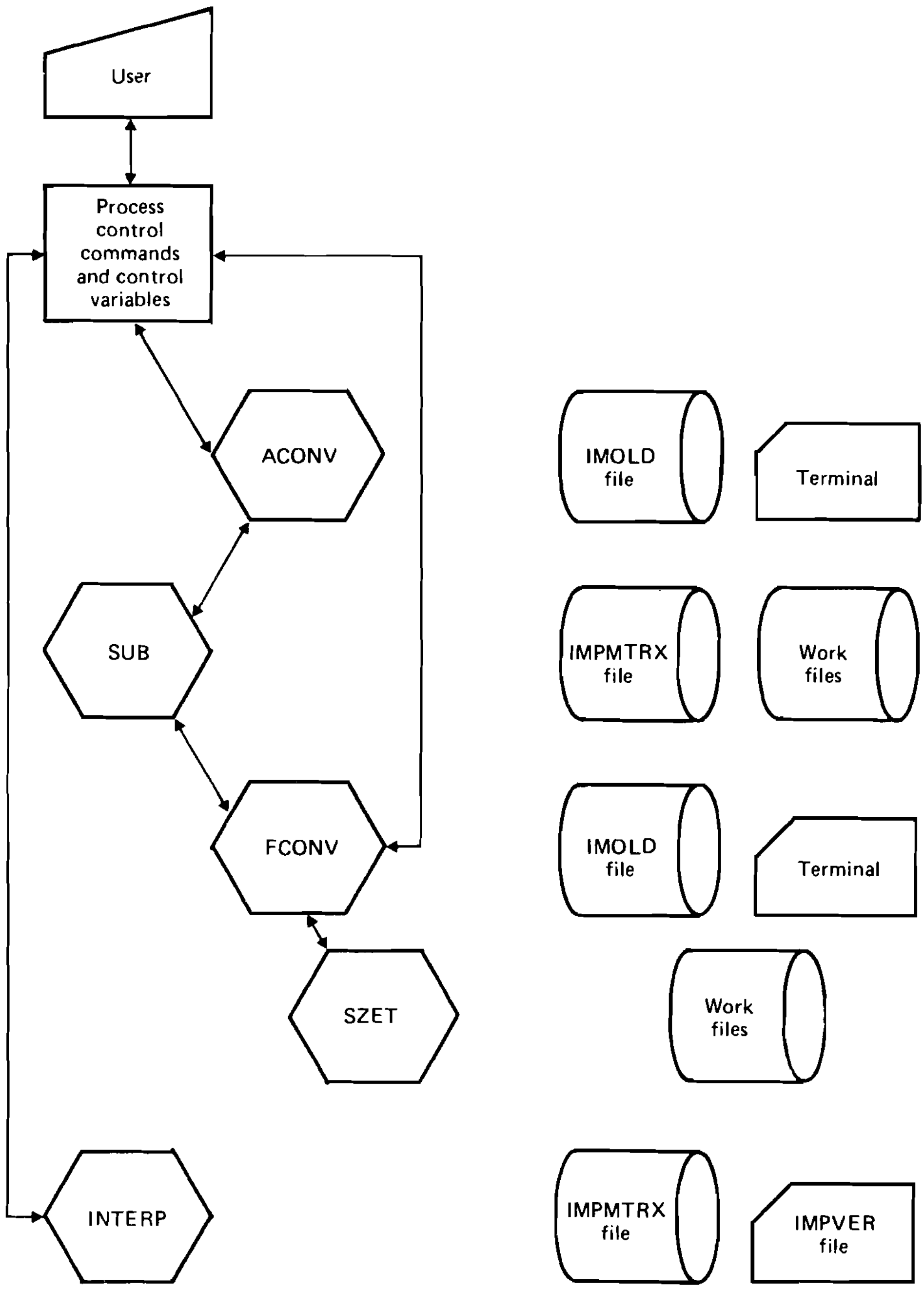

FIGURE 8 Program IMSETUP.

4.2.2.4 SUBROUTINE INTERP

Subroutine INTERP opens and reads file IMPVER which contains exogenous values for $\overline{X}_e$ and $\overline{Z}_e$. For the setup of the data deck of file IMPVER see Section 5.2.2. The values for $\overline{X}_e$ are given for every nth year; if the step size n is greater than 1, subroutine INTERP interpolates linearly the values for the other years. The values for $\overline{Z}_e$ are given as the sum of additional capacity values of n consecutive years. If step size n is greater than 1, subroutine INTERP distributes these values over the other years by a prescribed distribution function, which can be changed temporarily by the control command DISTR.

4.2.3 Program IMSOLVE

Program IMSOLVE, which is the third component of the interactive IMPACT system for the VM/370-CMS environment, is designed to solve IMPACT. Program IMSOLVE uses data file IMPMTRX produced by program IMSETUP.

The equations of the model are normalized for each of the endogenous variables. The two groups of endogenous variables are

- $X(t)$, the vector of output of energy-related sectors in the year t
- $Z(t)$, the vector of new additional capacities of energy-related sectors in the year t

The equation system consists of linear equations, which are normalized for vector $X(t)$, and of nonlinear equations, which are normalized for vector $Z(t)$. The linear equations are divided into a constant part and a function part. The constant part contains predetermined variables and parameters; the function part contains current endogenous variables and their coefficients.

The equation for time period t can be expressed as

$$X(t) = AX(t) + f(y(t))$$

where

- $AX(t)$ is the function part of the equation
- $f(y(t))$ is the constant part of the equation
- $X(t)$ is the vector of an endogenous variable
- $y(t)$ is the vector of predetermined variables consisting of exogenous vectors $\overline{X}_e(t)$ (annual energy production in the year t)

and $\overline{Z}_e(t)$ (required additional capacities in the ESS in the year t), and of endogenous vector $Z(t)$ whose values are computed by the nonlinear equations

The nonlinear equations normalized for vector $Z(t)$ have the following format at time period t:

$$Z(t) = \max \left[\min_{t_0 \leqslant \tau \leqslant t} (X(t+1) - X(\tau)); 0 \right]$$

where t_0 denotes the starting time period.

From the point of view of the algorithm, these nonlinear equations are not real equations requiring solution, since the values of vector $Z(t)$ are determined from the values of vector $X(t)$ which are computed by the linear equations.

The major iteration of the algorithm is composed of two phases:

Phase 1: Solving the linear equation system for every time period with predetermined values of vector $Z(t)$ (The Gauss–Seidel procedure, which solves the subsystem for a given time period t, is called a minor iteration.)
Phase 2: Computing the values of vector $Z(t)$ from the values of vector $X(t)$ obtained by phase 1

The major iteration process should be repeated until values of both vectors $X(t)$ and $Z(t)$ are found to a given accuracy.

Program IMSOLVE consists of a main program with 16 subroutines. The subroutines are as follows:

Model input level

OLV (inputs matrices A, $F^{(0)}, \ldots, F^{(\hat{\tau})}$)
ZNAM1 (inputs product names)
DEFX (inputs vectors $\overline{X}_e(t)$ and $\overline{Z}_e(t)$)

Algorithm

DINSOL (controls the major iteration)
ZB (sets up the right-hand side of the linear equation system at a given time period t)
SOLS (solves the linear subsystem)
ZN (computes new additional capacities for all sectors)
DEC (auxiliary procedure)

Model output level

PRISOL (generates the solution from files recorded by algorithm procedures)
FILW (auxiliary subroutine for subroutine PRISOL)
TABL (displays matrices in tabular form)
LISTX (auxiliary subroutine for subroutine TABL)
LISTAZ (auxiliary subroutine for subroutine TABL)
CUT (auxiliary subroutine for subroutine TABL)
BILD (plots the solution)
SOS (displays error messages)

Figure 9 is a flow chart of the major subroutines and files of program IMSOLVE; Figure 10 is a flow chart of the algorithm.

4.2.3.1 MAIN PROGRAM

The main program opens data file IMPMTRX and initializes the parameters required for the solution. Subroutines OLV, ZNAM1, and DEFX read, respectively, the coefficients of matrices A, $F^{(0)}$, ..., $F^{(\hat{\tau})}$, the product names, and the exogenous vectors $\overline{X}_e(t)$ and $\overline{Z}_e(t)$. The initial values of output $X(t)$ and of capacity $Z(t)$ are either read from file IMBASIS by subroutine DEFX (which could have been created by the previous run of program IMSOLVE containing the model solution) or they are set to zero. After all necessary parameters have been entered, the program calls subroutine DINSOL. Control is returned to the main program after a solution has been found to the specified accuracy or the limit on the number of major or minor iterations has been reached. At this time the user can make changes to the parameters and continue, or he can print the results and quit.

4.2.3.2 SUBROUTINE DINSOL

Subroutine DINSOL manages the major and minor iterations of the algorithm. A major iteration consists of solving a linear equation system for every time period and then computing new additional capacities for all sectors. During a minor iteration step, subroutine ZB is called to calculate the right-hand side of the linear equation system at a given time period. Thereafter program IMSOLVE calls subroutine SOLS. Control is

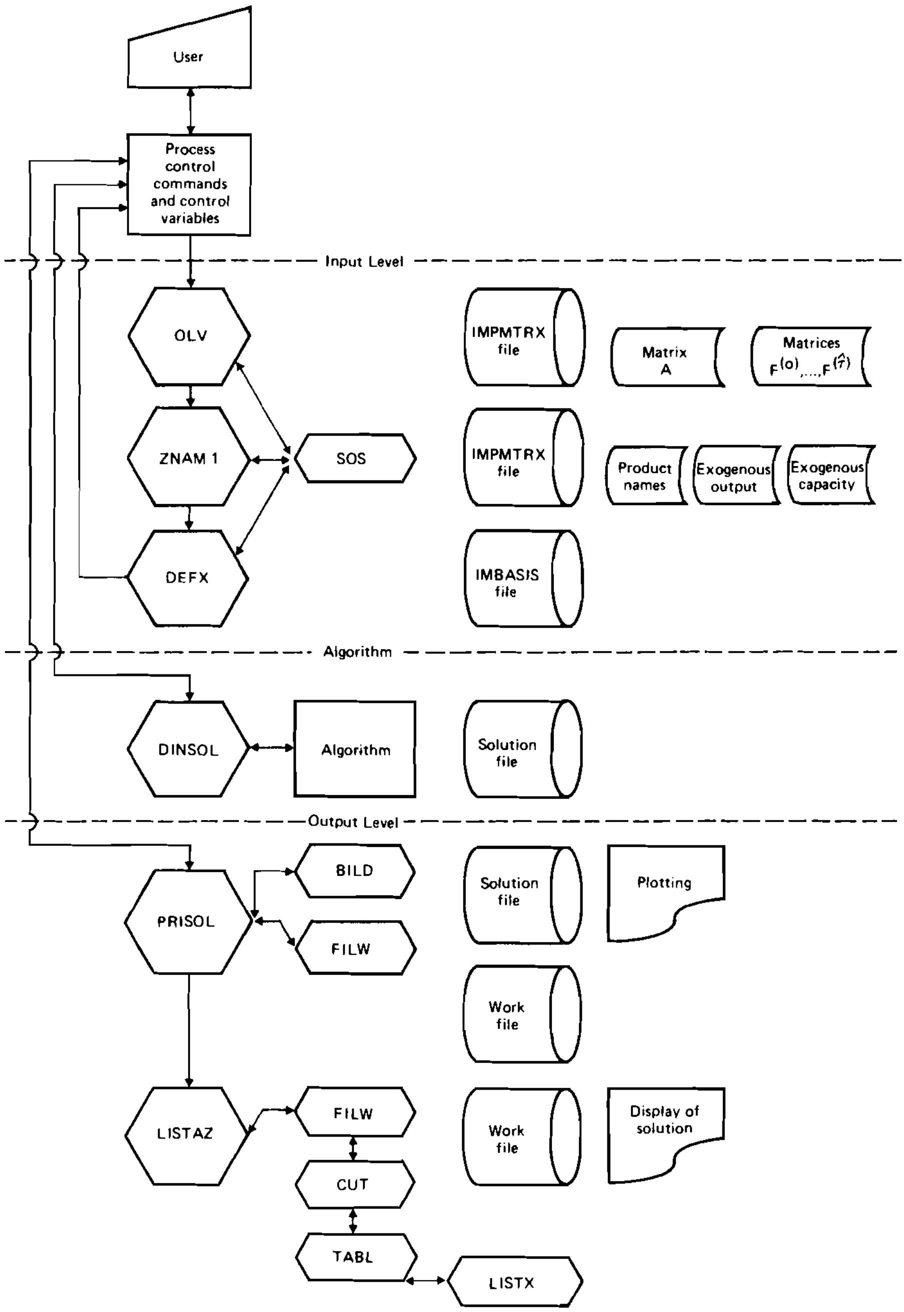

FIGURE 9 Program IMSOLVE.

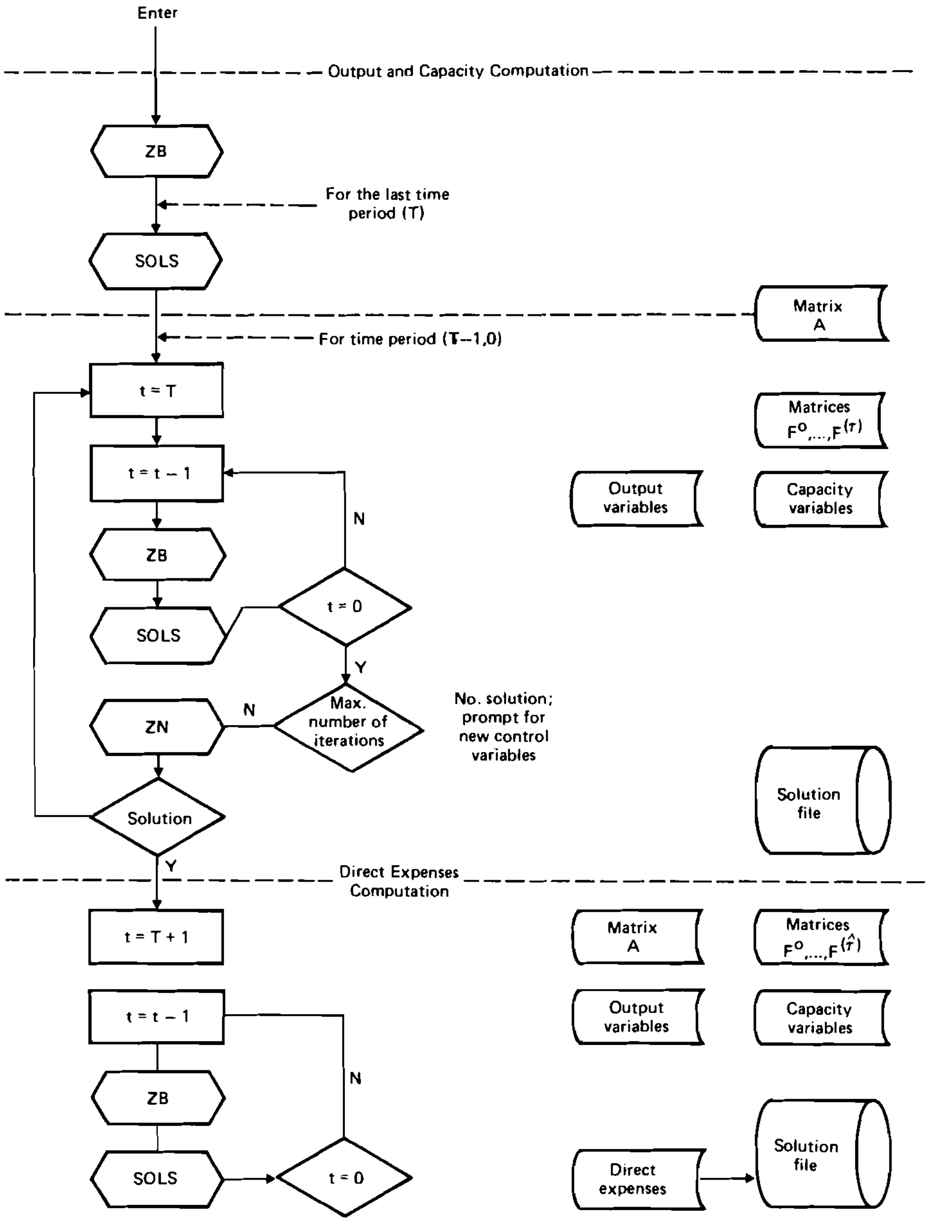

FIGURE 10 Algorithm of the IMPACT model system.

returned to subroutine DINSOL after a solution has been found to the linear equation system.

After the minor iteration step has been carried out for every time period, the program calls subroutine ZN to compute the values of new additional capacities for all sectors. After the solution to the model is found, the solution vectors are recorded and the direct expenses are calculated for every time period by calling subroutines ZB and SOLS.

4.2.3.3 SUBROUTINE ZB

Subroutine ZB is used to set up the right-hand side of the linear equation system at a given time period. This is computed from the following:

$\overline{X}_e(t)$, the vector of annual energy production in the year t
$\overline{Z}_e(t)$, the vector of required additional capacities in the ESS in the year t
$Z(t)$, the vector of new additional capacities in energy-related sectors in the year t
matrix $F_3{}^{(\tau-t)}$, whose coefficients are the capital investments in the year t to put into operation the capacities of the ESS and the energy-related sectors in the year τ

4.2.3.4 SUBROUTINE SOLS

Subroutine SOLS manages the solution to the linear equation system at a given time period t by means of the Gauss–Seidel procedure. If the model is solved for 75 periods, then subroutine SOLS is called 75 times during one major iteration step.

4.2.3.5 SUBROUTINE ZN

Subroutine ZN is called from subroutine DINSOL at the end of a major iteration step in order to compute new additional capacities for all sectors.

4.2.3.6 SUBROUTINE PRISOL

After a solution to the model system has been obtained, subroutine PRISOL is called upon to prepare it for direct printing; thereafter subroutine LISTAZ and/or subroutine BILD is called upon to display the solution in tabular form and/or in the form of plotted time functions.

5 USER GUIDE

5.1 RUNNING PROGRAM IMDATA

5.1.1 Prompting Sequence

At the beginning of each run, IMDATA prompts the user for the control commands and for the values of the control variables which hold the information needed to run the problem.

There are three types of control:

- Control commands, which regulate the execution of the tasks
- General information control variables, which contain the user's choice of model parameters – e.g., size of the matrices, lag value
- Parameter control variables, which are the parameters for the program

Each control variable has a default setting. The default setting, along with the description of its prompt, is given below. In order to specify the default value, the user hits the return key in response to the prompt. All prompts requiring a YES or a NO response have a default YES. The initial prompts appear at the user terminal in the order given below, and should be responded to as indicated.

5.1.1.1 CONTROL COMMANDS

ENTER THE LEVEL DESIRED. The level of input indicates whether to input new matrices or to update existing ones. The different levels and the corresponding control commands are given below.

Input Level. New coefficient matrices are read from file IMPCOEF and a new data file IMOLD is created. The control command for INPUT has the form INPUT [one or more options], where any one of the following options is possible:

OLD: converted data are written to the file IMOLD rather than to file IMNEW.
NEW: the updated matrices are directed to file IMNEW; but this option is default.
ERR: in the presence of an input error during the input level, the data file IMOLD is not created. *Default*: the data file IMOLD is created if there are no fatal errors.
NOPROM: default values are set for all parameter variables rather than prompt for their values. Prompting for general information control variables is not suppressed.

Modify Level. Existing data file IMOLD is revised. The control command for MODIFY has the form MODIFY [one or more options] where any one of the following options is possible:

OLD: updated matrices are copied back to file IMOLD rather than copied to file IMNEW.
NEW: the updated matrices are directed to file IMNEW; but this option is default.
ERR: in the presence of an error during the modify level, the matrix updating is not carried out; the entire revise deck is processed in order to catch as many errors as possible. *Default*: the updated file IMOLD is produced if there are no fatal errors.
NOPROM: default values are set for all parameter variables rather than prompt for their values. Prompting for general information control variables is not suppressed.

Output Level. The program displays on the standard printing device the entire matrices or selected parts thereof. The control command for OUTPUT has the form LIST [one or more options] where any one of the following options is possible:

OLD: matrix coefficients are retrieved from file IMOLD rather than from file IMNEW.
NEW: default.

NOPROM: default values are set for all parameter variables rather than prompt for their values.

5.1.1.2 GENERAL INFORMATION CONTROL VALUES

ENTER THE NAME OF THE INPUT DECK. The first card of the data deck contained in file IMPCOEF is always a NAME card, which gives a user-specified name to the data deck so that the data may be identified. After the user enters a name, the program compares it with the name given on the NAME card. An incorrect name results in a "failure to open file" error, and the prompt asking for the name of the data deck reappears. This prompt appears only at the input and modify levels.

DO YOU WISH TO USE INDEX INSTEAD OF NAME. This prompt appears only at the input and modify levels. The elements of the matrices in file IMPCOEF are identified either by name or by index. If names are used to identify matrix elements, then either file IMPCOEF has a PRODUCTS section defining the sequence of the product names, or file IMOLD contains a set of product names defined in a previous run. YES is typed if indices have been used in file IMPCOEF. NO is typed if names have been used. *Default*: YES.

ENTER THE ORDER OF MATRICES. This prompt specifies the order of matrices A, C, $S_0, \ldots, S_{\hat{T}}$. *Default*: use either the value of the order stored in file IMOLD, if it exists, or 156.

ENTER THE LAG VALUE. This defines the maximum number of S_i matrices stored in file IMOLD. *Default*: use either the lag value stored in file IMOLD, if it exists, or 6.

5.1.1.3 PARAMETER CONTROL VARIABLES

ENTER THE ZERO TOLERANCE. This specifies the tolerance below which a matrix element is set to zero. The tolerance value is 10^{-S}, where S is the number specified by the user. *Default*: 8.

ENTER THE NAME OF THE MATRIX TO BE PRINTED. This prompt, which appears only at the output level, specifies the name of the matrix to be printed. The possible choices are:

A for A matrix
C for C matrix
$S0$ for S_0 matrix

$S1$ for S_1 matrix
:
$S6$ for S_6 matrix

Default: A

ENTER THE INDEX OF THE SUBMATRIX TO BE PRINTED. This prompt, which appears only at the output level, determines the submatrices of the above specified matrix which should be printed. The indexing of the submatrices is shown in Figures 4 and 5. *Default*: all. (All submatrices of the above defined matrix will be printed.) After the level has been chosen by means of a control command and the control variables have been entered, the system prompts one of the following messages according to the chosen level:

AT LEVEL INPUT. NEXT?
AT LEVEL MODIFY. NEXT?
AT LEVEL LIST. NEXT?

The answer can be any one of the following options: EXEC, CONTINUE, RESTART, or STOP. By entering command EXEC, the system completes its work at the defined level and returns with one of the three prompts defined above. By entering command CONTINUE, the system remains at the same level, but restarts prompting for the parameter variables. By entering command RESTART, the system restarts with the prompt ENTER THE LEVEL DESIRED. By entering command STOP, the program closes all the files and finishes off.

5.1.2 Format of Data Cards and Organization of Data Deck for File IMPCOEF

The data file IMPCOEF for the INPUT and the MODIFY procedures contains four types of cards in all cases:

- A NAME card, which is always the first in a data deck
- Section-header cards, which specify the type of data that follows
- Data cards, which contain the actual data values
- An EOJ card, which is always the last card in a data deck

Comment cards, identified by a character *C* in column 1, may be inserted anywhere in a data deck.

5.1.2.1 NAME CARDS

The NAME card gives a user-specified name to the data decks so that the data may be identified. A NAME card has the following format:

Columns 1–4: NAME
Columns 9–16: name assigned by user

The name may contain from one to eight characters.

5.1.2.2 SECTION-HEADER CARDS

The data deck consists of data cards grouped according to the type of data they contain; a group of cards containing similar type of data is called a section. The first card of a section is always a section-header card identifying the type of data in that section. The types of data in a data deck are: PRODUCTS, A-MATRIX, and F-MATRIX. Section-header cards contain only one word specifying the type of data cards that follows. The first character must be in column 1.

5.1.2.3 DATA CARDS

Data cards are divided into "fields" – that is, consecutive card columns. The section-header card determines the field structure of the data cards. The three types of data cards are discussed below.

Product-Name Data Cards. PRODUCTS data cards specify the product names to be assigned to the rows and columns of the matrix. Because the ith row refers to the same product as that in the ith column, the product names should be defined only for the rows.

The format of a PRODUCTS data card is:

Columns 1–4: blanks
Columns 5–10: product names

In columns 5 to 10, blanks are considered characters and are not suppressed.

A-MATRIX Data Cards. A-MATRIX data cards define the actual value of the matrix elements in terms of row vectors. It is not necessary to specify the value if the coefficient is zero. The format of the A-MATRIX data card is shown in Table 3.

Field 1 gives the name or the index of the row that contains the elements specified in the fields that follow. Field 2 contains the name or the index of a column in which an element is to be entered. Field 3 contains the value of the element to be entered in the column and in the row of fields 1 and 2. Field 4 is optional and is used like field 2. Field 5 is optional and is used like field 3. Fields 6 to 9 are optional and are used like fields 2 and 3. All names in fields 1, 2, 4, 6, and 8 of the data card must consist of from one to six alphanumeric characters. If the fields give indices, then these should be numeric values. The matrix elements must be specified by rows – that is, all coefficients referring to the same row name (field 1) must be contiguous.

F-MATRIX Data Cards. *F*-MATRIX data cards specify the actual values of matrices $C, S_0, \ldots, S_{\hat{\tau}}$. The format of the *F*-MATRIX data card is shown in Table 4.

Field 2 identifies the name or the index of the row. Field 3 identifies the name or the index of the column of the matrices $C, S_0, \ldots, S_{\hat{\tau}-1}$, and $S_{\hat{\tau}}$ in which the elements specified in fields 4 to 7 are to be entered.

If the time lag τ is greater than 5, then the values of matrices C, S_0 $\ldots, S_{\hat{\tau}}$ should be defined by more than one card. The first card, which contains a blank field 1, defines the values of matrices $C, S_0, S_1, S_2, \ldots,$ S_5; the continuous cards, which contain the character * in field 1, define the values of matrices $S_6, \ldots, S_{\hat{\tau}}$.

All matrix elements must be specified by rows – that is, when one element is given, all other elements in that row where the element of matrix C is other than zero must also be entered before another row can be mentioned. Zero entries should not be specified because they will be filled in automatically by the system.

5.1.2.4 EOJ CARDS

The EOJ card, which indicates the end of the data deck, has the following format:

Columns 1–3: EOJ

5.2 RUNNING PROGRAM IMSETUP

5.2.1 Prompting Sequence

At the beginning of each run, IMSETUP prompts the user for the control commands and for the values of the control variables which hold the information needed to run the problem.

TABLE 3 Format of A-MATRIX data cards for file IMPCOEF.

Field	Column	Content
1	5–10	Name or index
2	12–17	Name or index
3	18–25	Value
4	26–31	Name or index
5	32–39	Value
6	40–45	Name or index
7	46–53	Value
8	54–59	Name or index
9	60–67	Value

TABLE 4 Format of F-MATRIX data cards for file IMPCOEF.

Field	Column	Content
1	1	Blank or *
2	5–10	Name or index
3	12–17	Name or index
4	18–25	Value
5	26–33	Value
6	34–41	Value
7	42–49	Value
8	50–57	Value
9	58–65	Value
10	66–73	Value

There are three types of control:

- Control commands, which regulate the execution of the tasks
- General information control variables, which contain the user's choice of model parameters – e.g., size of matrices, lag value
- Parameter variables, which are the parameters for the program

Each control variable has a default setting. The default setting, along with the description of its prompt, is given below. In order to specify the default values, the user hits the return key in response to the prompt. All prompts requiring a YES or a NO response have a default YES. The initial prompts appear at the user terminal in the order shown below, and should be responded to as indicated.

5.2.1.1 CONTROL COMMANDS

Three commands are recognized by program IMSETUP. These can be entered only after the system has prompted the message ENTER CONTROL COMMANDS and the character * has appeared on the line following the above message. After a command has been issued from the terminal, the response is always the character *. If no additional control commands are to be entered, then the user hits the return key on a blank line, i.e., nothing is typed after the last carriage return.

The following control commands are accepted: CHANGE, DISTR, STOP.

The control command CHANGE is used if the user wishes to change the coefficient of the matrices A, C, S_0, ..., $S_{\hat{\tau}}$ for only one model run without changing the data in file IMOLD. The control command CHANGE has the form CHANGE [one or more options] where any one of the following options is possible:

- *A*: temporary changes are made in matrix A; *default*: no changes
- *C*: temporary changes are made in matrix C; *default*: no changes
- *SO*: temporary changes are made in matrix S_0; *default*: no changes
- *SN*: temporary changes are made in matrix S_N; symbol N represents any integer value in the range $[1,\hat{\tau}]$; *default*: no changes

If control command CHANGE was issued from the terminal, the program will ask to enter the modifications by prompting the message ENTER MODIFICATIONS FOR MATRIX "name", where name represents one of the matrix names used as one of the arguments of the control command CHANGE. These messages appear only after all prompts for values of the control variables have been answered. The modifications for matrices should be entered in the format of an A-MATRIX data card. In order to return to the program, the user hits the return key on a blank line, i.e., nothing is typed after the last carriage return. Then the program prompts for confirmation of the modification MODIFICATIONS CONFIRMED? YES/NO. NO is typed if the user wishes to repeat the modification phase.

The control command DISTR is used if the user wants to change the distribution function by which the sum of additional capacities is distributed over a given time interval. The command DISTR has the form DISTR [n] where the integer value n represents the value of the step size, i.e., the length of the distribution vector. *Default*: 5. The distribution vector is entered in response to the prompt ENTER DISTRIBUTION VECTOR. The actual values of the distribution are typed in as many lines as the dimension of the distribution vector. The values are entered in the first 12 positions of the line. After receiving the last value, the program prompts VALUES CONFIRMED? YES/NO. In the presence of any error in typing, the answer is NO, in which case the user can retype the whole distribution vector. In order to stop the execution of the program, the user commands STOP.

5.2.1.2 GENERAL INFORMATION CONTROL VARIABLES

ENTER THE NAME OF THE INPUT DECK. The first card of the data deck contained by file IMPVER is always a NAME card. The NAME card gives a user-specified name to the data deck so that the data may be identified. After entering a name chosen by the user, the program compares it with the name given on the NAME card. An incorrect name results in a "failure to open file" error, and the prompt asking for the name of the data deck reappears: DO YOU WISH TO USE INDEX INSTEAD OF NAME. The exogenous energy productions in file IMPVER are identified either by name or by index. YES is typed if the user has used indices in file IMPVER; NO is typed if the user has used names. *Default*: YES.

ENTER THE LAG VALUE. This defines the number of $F^{(\tau)}$ matrices for setting up the solution to the model.

ENTER THE STARTING YEAR. This defines the starting year of the time interval during which the model is solved. *Default*: 1975.

ENTER THE FINISHING YEAR. This defines the upper limit of the time interval during which the model is solved. *Default*: 2028.

5.2.1.3 PARAMETER CONTROL VARIABLES

ENTER THE ZERO TOLERANCE. This specifies the tolerance below which an element is set to zero. The tolerance value is 10^{-S}, where S is the number specified by the user. *Default*: 8.

5.2.2 Format of Data Cards and Organization of Data Deck for File IMPVER

The data file IMPVER for the SETUP procedure contains four types of cards:

- A NAME card, which is always the first in a data deck
- Section-header cards, which specify the type of data that follows

- Data cards, which contain the actual data values
- An EOJ card, which is always the last card in a data deck

Comment cards, identified by a character *C* in column 1, may be inserted anywhere in a data deck.

5.2.2.1 NAME CARDS

The NAME card gives a user-specified name to the data decks so that the data may be identified. It has the following format:

Columns 1–4: NAME
Columns 9–16: name assigned by user

The name may contain from one to eight characters.

5.2.2.2 SECTION-HEADER CARDS

The data deck consists of data cards grouped according to the type of data they contain; a group of cards containing similar type of data is called a section. The first card of a section is always a section-header card identifying the type of data in that section. The types of data in a data deck are: OUTPUT and CAPACITY. Section-header cards contain only one word specifying the type of data cards that follows. The first character must be in column 1.

5.2.2.3 DATA CARDS

Data cards are divided into ten fields. The type of data cards as defined by the section cards determines the content of each field, but all data cards follow the same general format. In this section, field 1 always refers to card columns 3 to 8; field 2 to card columns 10 to 13; and so on. The format of the data cards is shown in Table 5.

All the names contained in field 1 of the data cards must consist of from one to five alphanumeric and special characters. Eleven characters, which include a decimal point, define all numeric values appearing in fields 2 to 8. Specification of a sign is optional. If a sign is not specified, the plus sign (+) is implied. Values presented without a decimal point are interpreted as integers. Floating point format is also acceptable—that is, the Fortran "E" type format.

OUTPUT Data Cards. OUTPUT data cards specify the product name or the index of the energy production variables ($\overline{X}_e(t)$). Further, they define the actual value of the elements of these variables over the time interval $[T_1, T_2]$. Both years T_1 and T_2 are specified by control variables.

The actual values of elements of the variables are defined in terms of vectors; the length of these vectors is equal to the length of the time interval $[T_1, T_2]$.

The format of the OUTPUT data card is shown in Table 6.

Fields 5 to 8 are optional and are used only if the values defined by them are not zeros. All OUTPUT data cards referring to the same energy production must be contiguous, and the year on these cards should be increasing with respect to the order of the data cards. Energy production vectors with zero elements for every time period should not be specified, because they will be filled in automatically by the system. If the step size (field 3) is greater than 1, then the values for the other years are interpolated linearly.

CAPACITY Data Cards. CAPACITY data cards specify the values of the exogenous vector $\overline{Z}_e(t)$. The values of $\overline{Z}_e(t)$ are defined over the time interval $[T_1, T_2]$. Both years, T_1 and T_2, are defined by control variables.

The format of the CAPACITY data card is shown in Table 7.

Fields 5 to 8 are optional and are used only if the values defined by them are not zeros. All CAPACITY data cards referring to the same energy production must be contiguous and the year on these cards should be increasing with respect to the order of the data cards. Energy production with zero additional capacities for every year should not be specified, because they will be automatically filled in by the system. If the step

TABLE 5 Format of data cards for file IMPVER.

Field	Column	Content
1	3–8	Name or index
2	10–13	Integer value
3	15–16	Integer value
4	17–24	Value
5	25–32	Value
6	33–40	Value
7	41–48	Value
8	49–56	Value

TABLE 6 Format of OUTPUT data cards for file IMPVER.

Field	Content
1	Product name or index
2	Year
3	Step size
4	Energy production in year "field 2"
5	Energy production in year "field 2 plus the step size"
6	Energy production in year "field 2 plus two times the step size"
7	Energy production in year "field 2 plus three times the step size"
8	Energy production in year "field 2 plus four times the step size"

TABLE 7 Format of CAPACITY data cards for file IMPVER.

Field	Content
1	Product name or index
2	Year (t)
3	Step size (n)
4	Sum of additional capacities over time interval $[t - n, t - 1]$
5	Sum of additional capacities over time interval $[t, t + n - 1]$
6	Sum of additional capacities over time interval $[t + n, t + 2n - 1]$
7	Sum of additional capacities over time interval $[t + 2n, t + 2n, t + 3n - 1]$
8	Sum of additional capacities over time interval $[t + 3n, t + 4n - 1]$

size (field 3) is greater than 1, then the capacity sums will be distributed by a prescribed distribution function over the time interval.

5.2.2.4 EOJ CARD

The EOJ card, which indicates the end of the data deck, has the following format:

Columns 1–3: EOJ

5.3 RUNNING PROGRAM IMSOLVE

5.3.1 Prompting Sequence

At the beginning of each run, IMSOLVE prompts the user for the control commands and for the values of the control variables which hold the information needed to run the problem.

There are three types of control:

- Control commands, which regulate the execution of the tasks
- General information control variables, which contain the user's choice of model parameters – e.g., the name of the model
- Parameter control variables, which are the parameters for the program

Each control variable has a default setting. The default setting, along with the description of its prompt, is given below. In order to specify the default value, the user hits the return key in response to the prompt. All prompts requiring a YES or a NO response have a default YES. The initial prompts appear at the user terminal in the order below, and should be responded to as indicated.

5.3.1.1 CONTROL COMMANDS

Five commands are recognized by program IMSOLVE. The commands can be entered only after the system has prompted the message ENTER CONTROL COMMANDS and the character * has appeared on the line following the above message. After a command has been issued from the terminal, the response is always the character *. If no additional control commands are to be entered, then the user hits the return key on a blank line, i.e., nothing is typed after the last carriage return.

The following control commands are accepted: INPUT, SOLUTION, RESULTS, PRINT, STOP.

For the INPUT command, coefficient matrices and exogenous values will be read from file IMPMTRX. The control command for INPUT has the form INPUT [options] where any one of the following options is possible:

RESTORE: starting values for the output sector (X) and for the capacity vector (Z) will be initialized by the values read from file IMBASIS rather than by initializing them to zero.

NOPROM: default values are set for all parameter variables rather than prompt for their values. Prompting for general information control variables is not suppressed.

For the SOLUTION command, the major algorithm begins by computing the values of the output and the capacity vectors. The control command for SOLUTION has the form SOLUTION [NOPROM]. If option NOPROM is specified, default values are set for all parameter variables rather than prompt for their values.

For the RESULTS command, direct expenses are computed using the the current values of the output and the capacity vectors. The control command for RESULTS has the form RESULTS [NOPROM]. If option NOPROM is specified, default values are set for all parameter variables rather than prompt for their values.

For the PRINT command, the solution is displayed in tabular form and in the form of plotted time functions. The control command for PRINT has the form PRINT [options] where any one of the following options is possible:

PLOT: plotting is required.
NOPROM: default values are set for all parameter variables rather than prompt for their values.

The control command STOP brings the execution of the program to a close. The control command for STOP has the form STOP [SAVE]. If option SAVE is specified, the current values of output (X) and capacity (Z) vectors are stored in file IMBASIS.

5.3.1.2 GENERAL INFORMATION CONTROL VARIABLES

Prompts for general information control variables appear only after an INPUT control command has been issued.

ENTER THE NAME OF THE PROBLEM. In the setup level the name given on the NAME card of file IMPVER is stored in file IMPMTRX so that the model file may be identified. After the user has entered a name, the program compares this name with that stored in file IMPMTRX. An incorrect name results in a "failure to open file" error, and the prompt asking for the name of the model file reappears: DO YOU WISH A SHORT STATISTIC. If YES is typed, then a short statistic of the model parameter is displayed on the terminal.

5.3.1.3 PARAMETER CONTROL VARIABLES

ENTER THE NUMBER OF SIGNIFICANT DIGITS DESIRED AT THE FINAL SOLUTION. This determines the accuracy desired of the major algorithm. The algorithm terminates when the relative difference between two successive approximations is less than 10^{-S} for each element of output vector X, where S is the number of digits specified by the user. *Default*: 3.

ENTER THE MAXIMUM NUMBER OF MAJOR ITERATIONS. This sets an upper limit on the number of major iterations in the algorithm. Should the limit be exceeded before the specified accuracy has been reached, the user will be given the option to either terminate (STOP command) or specify a new maximum and continue. *Default*: 20.

ENTER THE NUMBER OF SIGNIFICANT DIGITS DESIRED AT THE SOLUTION OF THE SUBSYSTEM. This determines the accuracy desired for the Gauss–Seidel procedure. The Gauss–Seidel algorithm terminates when the difference between two successive approximations is less than 10^{-S} for each coordinate, where S is the number of digits specified by the user. *Default*: 5.

ENTER THE MAXIMUM NUMBER OF MINOR ITERATIONS. This sets an upper limit on the number of Gauss–Seidel iterations. Should the limit be exceeded before the specified accuracy has been reached, the user will be given the option to either terminate or specify a new maximum and continue.

ENTER THE ZERO TOLERANCE. This specifies the tolerance below which an element is set to zero; the tolerance is 10^{-S}, where S is the number specified by the user.

Appendix A

DATA BASE OF IMPACT

The selection of the energy sectors and of the energy-related sectors included in the model, as well as the completeness and the quality of the data, depend on the purposes of the model and the time horizon being considered. For example, the version of IMPACT that was used at the Siberian Power Institute for 15-year planning purposes consisted of about 50 energy activities and 60 energy-related activities. The IIASA version of the model, which is used to evaluate and compare long-range energy strategies for up to 50 years for 7 world regions, includes about 60 energy activities and about 30 activities for the energy sectors. The sectoral composition of IMPACT as it exists at IIASA is shown in Table A.1.

Each of the sectoral activities is characterized by the following indices:

- Input coefficient per unit of output (operation and maintenance requirements for some materials, equipment, and services)
- Capital coefficient (some material and equipment requirements per unit of new capacity or per dollar of capital investment)
- Incremental capital/output ratios (specific investment per unit of new capacity)
- WELMM coefficients (specific expenditures of water, energy, land, manpower, and some limited materials for operation and construction)
- Typical construction time
- Pattern of lags between construction expenditures and completion of the plant

In IMPACT, as in any energy-oriented model, the accuracy required of the data for energy activities must be higher than that required for the energy-related sectors. Therefore in the construction of the data base of IMPACT particular attention was paid to the energy part of the data base. Many different sources were analyzed and used, among them data received from the Bechtel Corporation in the U.S. and from the IIASA WELMM group.

TABLE A.1 Sectoral composition of IMPACT.

Number	Name	Abbreviation	Unit
Energy sectors			
1	Nonconventional oil	OIL 3	10^6 t
2	Nonexpensive oil	OIL 1	10^6 t
3	Intermediate oil	OIL 1A	10^6 t
4	Oil import	OILIMP	10^6 t
5	Z Z Z[a]		
6	Gas import	GASIMP	10^9 m^3
7	Oil pipelines	OILPIP	10^6 t
8	Oil shale mine	OILSHL	10^6 t
9	Oil shale retorting and upgrading	SHLOIL	10^6 t
10	Expensive oil	OIL 2	10^6 t
11	High-gasoline refinery	OILREF	10^6 t
12	Biogas	BIOGAS	GW(th)
13	Petroleum products: pipelines and marketing	PRPIP	10^6 t
14	Intermediate gas	GAS 1A	10^9 m^3
15	Expensive gas	GAS 2	10^9 m^3
16	Nonconventional gas	GAS	10^9 m^3
17	Gas pipelines	GASP	10^3 km
18	Cheap gas	GAS 1	10^9 m^3
19	Methanol from natural gas	MTHGAS	10^6 t(oe)
20	Natural gas stockpiles	STCKPL	10^9 m^3
21	Cheap coal	COAL 1	10^6 t(ce)
22	Intermediate coal	COAL 1A	10^6 t(ce)
23	Expensive coal	COAL 2	10^6 t(ce)
24	Z Z Z[a]		
25	Coal gasification (high Btu)	CLGAS	10^9 m^3
26	Methanol from coal	MTHCL	10^6 t(oe)
27	Coal liquefaction and refinery	CLLIQU	10^6 t
28	Coal transportation 1 (train) (coal unit train 10500 t)	CLTPNS	train
29	Coal import	CLIMP	10^6 t
30	Coal slurry pipeline	SLPYPE	10^3 km
31	Conventional power plants	CLPWPL	GW(e)
32	Nonexpensive uranium	U203–1	10^6 t ore
33	Expensive uranium	U203–2	10^6 t ore
34	Uranium mill	UMILL	10^3 t U_3O_8
35	Uranium conversion	UCONV	10^3 t UF_6
36	Uranium enrichment	UENRCH	10^3 t SWU
37	LWR fuel fabrication	LWRFL	10^3 t
38	Light water reactor	LWR	GW(e)

TABLE A.1 *Continued.*

Number	Name	Abbreviation	Unit
39	Z Z Z[a]		
40	LWR fuel reprocessing	LWRRPR	10^3 t
41	FBR fuel fabrication	FBRFL	10^3 t
42	Fast breeder reactor	FBR	GW(e)
43	FBR fuel reprocessing	FBRRPR	10^3 t
44	HTGR fuel fabrication and reprocessing	HTGRFL	10^3 t
45	High temperature reactor	HTGR	GW(e)
46	Hydrogen, thermochemical	H2THRM	10^9 m^3
47	Hydrogen pipeline	H2PYPE	10^3 km
48	Solar power plant (tower)	SOLARE	GW(e)
49	Pump storage	PUMPST	GW(e)
50	Geothermal power complex	GEOTH	GW(e)
51	Solar heating	SOLARH	GW/yr
52	Nuclear coal gasification	NCLGAS	10^9 m^3
53	Hydrogen, electrolytic	H2ELEC	10^9 m^3
54	Hydropower plants (expensive)	HYDRO2	GW(e)
55	Hydrogen liquefaction and storage	H2LIQU	10^6 t
56	Electricity transmission and distribution	ELTRNS	GW(e)
57	Hydropower plants (nonexpensive)	HYDRO1	GW(e)
58	Gas distribution	GASDST	10^9 m^3
59	Plants with sulphur dioxide removal	SO2REM	GW(e)
60	District heat	DISHT	GW(th)
Energy-related sectors			
61	Iron ores mining	IRNORE	10^6 US$
62	Primary iron and steel manufacturing	IR+STL	10^6 US$
63	Fabricated metal products	MTLPRD	10^6 US$
64	Nonferrous metal ore mining	NFEROR	10^6 US$
65	Nonferrous metals manufacturing	NFERMT	10^6 US$
66	Chemical products	CHEMPR	10^6 US$
67	Plastic and synthetic materials	PLSTIC	10^6 US$
68	Petroleum products	PTRLPR	10^6 US$
69	Stone, clay and glass products	BLDMTR	10^6 US$
70	Lumber and wood products	LMBWOD	10^6 US$
71	Miscellaneous materials	MSCLMT	10^6 US$
72	Total materials	TOTMT	10^6 US$
73	Engines and turbines	ENGIN	10^6 US$
74	Electrical equipment	ELEQP	10^6 US$
75	Mining equipment	MINEQP	10^6 US$

TABLE A.1 *Continued.*

Number	Name	Abbreviation	Unit
76	Oil field equipment	OILEQP	10^6 US$
77	Construction equipment and machineries	CNSEQP	10^6 US$
78	Material handling equipment	MHNDL	10^6 US$
79	Metalworking machineries	MWDRK	10^6 US$
80	Instrumental and control	INSTR	10^6 US$
81	Transportation equipment	TRNEQP	10^6 US$
82	Special industry equipment	SPCEQP	10^6 US$
83	General industry equipment	GENEQP	10^6 US$
84	Fabricated plate products	PLTPRD	10^6 US$
85	Miscellaneous equipment	MISEQP	10^6 US$
86	Total equipment	TOTEQP	10^6 US$
87	Z Z Z[a]		
88	Z Z Z[a]		
89	Export goods I	EXPRT1	10^9 US$
90	Export goods II	EXPRT2	10^9 US$
91	Construction in energy sectors	ENCNST	10^9 US$
92	Construction (energy-related)	CNSTRC	10^6 US$
93	Transport (energy-related)	TRNSP	10^6 US$
94	Maintenance and repair construction	M+REPR	10^6 US$
95	Trade	TRADE	10^6 US$
96	Communication	CMUNIC	10^6 US$
CAPITAL INVESTMENT			
Energy supply system (direct investment)			
97	Oil industry	OILINV	10^6 US$
98	Natural gas industry	GASINV	10^6 US$
99	Coal industry	CLINV	10^6 US$
100	Synthetic fuel industry	SYNTET	10^6 US$
101	Fuel transportation	FLTRNS	10^6 US$
102	Fossil fuel fired power plants	PWRPL	10^6 US$
103	LWR	LWRIN	10^6 US$
104	FBR	FBRIN	10^6 US$
105	Fuel cycle	FLCICL	10^6 US$
106	Solar, geothermal, and hydropower plants	SOLGEO	10^6 US$
107	Electricity transmission and distribution	ELTRNS	10^6 US$
108	Hydrogen	H2	10^6 US$
109	Other direct investments	OTHER	10^6 US$
110	Total direct investment (construction and owner cost)	TOTDIR	10^6 US$

TABLE A.1 *Continued.*

Number	Name	Abbreviation	Unit
111	Total construction cost	CONSTC	10^6 US$
Energy-related sectors (indirect investment)			
112	Ferrous metallurgy and mining industry	FERMET	10^6 US$
113	Nonferrous metallurgy	NFRMET	10^6 US$
114	Building materials industry	BLDMTR	10^6 US$
115	Chemical industry	CHEMIN	10^6 US$
116	Machinery	MACH	10^6 US$
117	Other industries	OTHIND	10^6 US$
118	Nonenergy transport	TRNSP	10^6 US$
119	Building industry	BLDIND	10^6 US$
120	Export (to compensate fuel import)	EXPORT	10^6 US$
121	Total indirect investment	TOTIND	10^6 US$
WELMM			
Manpower			
122	Oil and gas extraction	MOILGS	10^3 person yr/yr
123	Coal mining	MCOAL	10^3 person yr/yr
124	Synthetic fuel production	MSYNT	10^3 person yr/yr
125	Fuel transportation and distribution	MFLTRN	10^3 person yr/yr
126	Electricity transmission and distribution	MELTRN	10^3 person yr/yr
129	Power generating	PWRGNP	10^3 person yr/yr
130	Total direct operating manpower	TOTDOP	10^3 person yr/yr
131	Indirect operation manpower	INDOP	10^3 person yr/yr
132	Direct construction manpower	DIRCNS	10^3 person yr/yr
133	Indirect construction manpower	INDCNS	10^3 person yr/yr
140	Unskilled labor (direct operating requirements	UNSILL	10^3 person yr/yr
Land			
127	Right-of-way	LNDTEM	km^2
128	Fixed	LNDPRM	km^2
Materials			
134	Steel	FERMET	10^6 t
135	Cement	CEMENT	10^6 t
136	Lead	LEAD	10^3 t
137	Copper	COPPER	10^3 t
138	Aluminum	ALUMIN	10^3 t
139	Water	WATER	10^6 m^3

TABLE A.1 *Continued.*

Number	Name	Abbreviation	Unit
Energy (indirect)			
141	Electric power	ELPWR	10^9 kWh
142	Motive power	MTVPWR	10^{12} Btu
143	Process heat	PRCHT	10^{12} Btu
144	Water and space heat	W+SHT	10^{12} Btu
145	Coal	COAL	10^{12} Btu
146	Gaseous fuels	GASFL	10^{12} Btu
147	Liquid fuels	LIQUFL	10^{12} Btu
Air pollution emission factors			
148	Particulates	PRTCL	t
149	NO_x	NOX	t
150	SO_x	SOX	t
151	CO	CO	t
152	Z Z Z[a]		
153	Z Z Z[a]		
154	Z Z Z[a]		
155	Hydrocarbons	HYDROC	t

[a]Sectors reserved for future use.

For the IIASA model, capital costs of extracting oil, natural gas, and coal in different world regions were evaluated, taking into account current marginal capital costs, known resources and their distribution by price categories, anticipated time of exhaustion of these resources, and other factors. Some of the results of this evaluation are given in Table A.2. The generalized material structure of the capital investment in fuels extraction is shown in Table A.3. These data, received from the analyses of different sources, were used for estimating corresponding capital coefficients.

Capital costs and other economic indices for power plants and energy conversion technologies do not depend greatly on local conditions as do the indices for primary energy resources. Therefore they were considered identical for all world regions, and were based on perspective data for the U.S.

As to input/output and capital coefficients for energy-related sectors, the evaluations for the various world regions and for the perspective of 30 to 50 years are very rough and aggregated. It is impossible to obtain average regional indices by means of conventional procedures of aggregation, because of the lack of corresponding data for all countries of the region. Therefore for each region we selected one representative country, aggregated its coefficients, and then generalized them for all regions. Thus, for example, the U.S. was considered the representative country for North America, the Federal Republic of Germany for Western Europe, and India for Southeast Asia.

TABLE A.2 Fuel capital costs in IMPACT (10^6 US$).

Resource cost category[a]		Unit	Region				
			North America	South America	Western Europe	Middle East	South-East Asia and Africa
Oil	1	10^6 t	145	175	180	50	150
	2	10^6 t	275	250	275	150	250
	3	10^6 t	405	350	440	360	385
	4	10^6 t	550	550	550	-	550
Gas	1	10^9 m^3	130	100	200	30	120
	2	10^9 m^3	335	300	375	95	320
	3	10^9 m^3	540	500	540	300	520
	4	10^9 m^3	790	790	790	-	790
Coal	1	10^6 tce	30	65	70	-	35
	2	10^6 tce	70	90	140	-	70
	3	10^6 tce	150	180	210	-	110

[a]Cost categories cover fuel resources from present marginal production cost (category 1) to $25/boe (category 4).

TABLE A.3 Fuel capital costs in IMPACT (in percentage).

	Oil		Gas		Coal	
	Onshore	Offshore	Onshore	Offshore	Underground	Surface
Materials	*33*	*30*	*36*	*33*	*15*	*5*
Primary iron and steel	15	12	14	17	3	1
Nonferrous metals					1	0.5
Fabricated metal products	3	12	2	9.5	7.5	1.5
Glass, clay, and stone products	7	2	13	3	1	1
Chemical and allied products	6	3	7	3	1.5	0.2
Miscellaneous materials	2	1	-	0.5	2	0.8
Equipment	*31*	*41*	*18*	*31*	*49*	*61*
Electrical	1	1	1	1	3.5	1.5
Oil field	20	34	9	24	-	-
Mining	-	-	-	-	32	52
Transportation and material handling					7.5	4.2
Fabricated plate products	4	1	3	1	2.5	2
General industry	3	1	2	1	1	0.3
Miscellaneous	3	4	3	4	2.5	1
Manpower	*26*	*13*	*28*	*18.5*	*22*	*19*
Services and other constructor costs	*10*	*16*	*18*	*17.5*	*14*	*15*
Total constructor's costs	100	100	100	100	100	100
Owner's costs in relation to constructor's costs	51	96	51	94	76	29

Appendix B

TEST CASE

The purposes of this appendix are to show the format of the IMPACT model printout, and to assist the potential user of the computer program.

One of the scenarios that was analyzed at IIASA for studying problems of the transition to new energy sources in different world regions is the so-called coal scenario for the North American region. The scenario is characterized by a nuclear moratorium – that is, the stopping of the construction of new nuclear power plants after the year 1985 – and the absence of constraints on coal production.

The following printout of IMPACT (Tables B.1–B.9) includes input and output data. Capital coefficients and specific material and equipment expenditures to build and operate energy facilities were taken for North America mainly from the Bechtel Corporation data base (Carasco *et al.*, 1975; Hogle *et al.*, 1976). Data for the energy-related sectors were compiled and aggregated from input/output tables for the U.S., prepared for the years 1967, 1970, 1985, and 2000 by the Bureau of Economic Analysis (1975), by the Center for Advanced Computation of the University of Illinois (Bullard and Pilati, 1975), and by the Brookhaven National Laboratory (Hogle *et al.*, 1976). The capital coefficients were obtained from the Bureau of Economic Analysis (1975b), and from the Battelle Memorial Institute (1971).

TABLE B.1 Energy sector, output, physical units.[a]

	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030
OIL1	0.578E+03	0.520E+03	0.600E+03	0.645E+03	0.698E+03	0.426E+03	0.0	0.0	0.0	0.0	0.0
OIL1A	0.0	0.0	0.0	0.0	0.0	0.234E+03	0.443E+03	0.338E+03	0.270E+03	0.173E+03	0.0
OILIMP	0.231E+03	0.300E+03	0.210E+03	0.180E+03	0.900E+02	0.110E+03	0.360E+03	0.460E+03	0.480E+03	0.580E+03	0.680E+03
OILPIP*	0.693E+03	0.670E+03	0.705E+03	0.735E+03	0.743E+03	0.715E+03	0.623E+03	0.568E+03	0.510E+03	0.500E+03	0.505E+03
OIL2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.373E+02	0.165E+03
OILREF	0.724E+03	0.734E+03	0.744E+03	0.753E+03	0.764E+03	0.776E+03	0.796E+03	0.789E+03	0.810E+03	0.836E+03	0.895E+03
PRPIP*	0.724E+03	0.734E+03	0.744E+03	0.773E+03	0.784E+03	0.846E+03	0.896E+03	0.939E+03	0.990E+03	0.102E+04	0.104E+04
GAS2	0.0	0.0	0.0	0.0	0.0	0.0	0.599E+03	0.678E+03	0.611E+03	0.603E+03	0.564E+03
GASTRI*	0.149E+04	0.157E+04	0.180E+04	0.196E+04	0.206E+04	0.215E+04	0.291E+04	0.271E+04	0.245E+04	0.241E+04	0.226E+04
GAS1	0.743E+03	0.783E+03	0.899E+03	0.982E+03	0.103E+04	0.107E+04	0.255E+03	0.0	0.0	0.0	0.0
STCKPL*	0.0	0.0	0.0	0.0	0.0	0.0	0.599E+02	0.678E+02	0.611E+02	0.603E+02	0.564E+02
COAL1	0.742E+03	0.954E+03	0.111E+04	0.133E+04	0.159E+04	0.0	0.0	0.0	0.0	0.0	0.0
COAL1A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.186E+04	0.233E+04	0.286E+04	0.312E+04
CLLIQU	0.0	0.0	0.0	0.200E+02	0.200E+02	0.700E+02	0.100E+03	0.150E+03	0.180E+03	0.180E+03	0.150E+03
CLTRNS*	0.111E+04	0.143E+04	0.167E+04	0.199E+04	0.239E+04	0.0	0.0	0.278E+04	0.350E+04	0.429E+04	0.468E+04
SLPYPE*	0.148E+03	0.191E+03	0.223E+03	0.265E+03	0.318E+03	0.0	0.0	0.928E+03	0.117E+04	0.143E+04	0.156E+04
CLPWPL	0.580E+03	0.711E+03	0.843E+03	0.959E+03	0.103E+04	0.100E+04	0.870E+03	0.729E+03	0.535E+03	0.343E+03	0.178E+03
U303-1	0.196E+01	0.194E+01	0.190E+01	0.176E+01	0.132E+01	0.0	0.0	0.0	0.0	0.0	0.0
UMILL*	0.771E+01	0.757E+01	0.713E+01	0.627E+01	0.472E+01	0.0	0.0	0.0	0.0	0.0	0.0
UCONV*	0.907E+01	0.889E+01	0.836E+01	0.732E+01	0.551E+01	0.0	0.0	0.0	0.0	0.0	0.0
UENRCH*	0.499E+01	0.491E+01	0.468E+01	0.418E+01	0.315E+01	0.0	0.0	0.0	0.0	0.0	0.0
LWRFL*	0.151E+01	0.148E+01	0.139E+01	0.122E+01	0.918E+00	0.0	0.0	0.0	0.0	0.0	0.0
L W R	0.389E+02	0.386E+02	0.377E+02	0.348E+02	0.262E+02	0.0	0.0	0.0	0.0	0.0	0.0
LWRRPR*	0.101E+01	0.100E+01	0.979E+00	0.906E+00	0.682E+00	0.0	0.0	0.0	0.0	0.0	0.0
SOLARE	0.0	0.0	0.0	0.0	0.999E+01	0.400E+02	0.110E+03	0.110E+03	0.116E+03	0.138E+03	0.182E+03
PUMPST	0.0	0.0	0.0	0.0	0.500E+01	0.200E+02	0.550E+02	0.550E+02	0.579E+02	0.689E+02	0.909E+02
SOLARH	0.160E+02	0.280E+02	0.400E+02	0.530E+02	0.650E+02	0.770E+02	0.890E+02	0.990E+02	0.108E+03	0.115E+03	0.122E+03
ELTRNS*	0.729E+03	0.868E+03	0.101E+04	0.114E+04	0.126E+04	0.133E+04	0.146E+04	0.164E+04	0.175E+04	0.173E+04	0.183E+04
HPWPL1	0.110E+03	0.118E+03	0.127E+03	0.137E+03	0.147E+03	0.156E+03	0.165E+03	0.173E+03	0.181E+03	0.188E+03	0.194E+03
GASDST*	0.743E+03	0.783E+03	0.899E+03	0.982E+03	0.103E+04	0.107E+04	0.854E+03	0.678E+03	0.611E+03	0.603E+03	0.564E+03
S2ORMV	0.0	0.0	0.0	0.999E+01	0.400E+02	0.110E+03	0.260E+03	0.570E+03	0.862E+03	0.994E+03	0.118E+04

[a]Units are defined in Appendix A. Asterisk indicates endogenous variables which are evaluated in the model run.

TABLE B.2 Energy sector, capacity, physical units.[a]

	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030
OIL1	0.573E+01	0.133E+02	0.114E+02	0.101E+02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OIL1A	0.0	0.0	0.0	0.0	0.130E+02	0.116E+02	0.0	0.0	0.0	0.0	0.0
OIL1MP	0.205E+02	0.0	0.0	0.0	0.0	0.0	0.305E+02	0.174E+02	0.340E+02	0.369E+02	0.438E+02
OILPIP*	0.156E+02	0.265E+02	0.265E+02	0.229E+02	0.161E+02	0.233E+01	0.713E+01	0.503E+01	0.129E+02	0.156E+02	0.523E+02
OIL2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.957E+01	0.710E+01	0.710E+01
OILREF	0.549E+01	0.802E+01	0.918E+01	0.106E+02	0.123E+02	0.615E+01	0.506E+01	0.927E+01	0.107E+02	0.141E+02	0.140E+02
PRPIP*	0.231E+02	0.233E+02	0.275E+02	0.247E+02	0.353E+02	0.346E+02	0.346E+02	0.376E+02	0.341E+02	0.353E+02	0.315E+02
GAS2	0.0	0.0	0.0	0.0	0.0	0.204E+02	0.196E+02	0.150E+02	0.150E+02	0.329E+02	0.329E+02
GASTR1*	0.594E+02	0.920E+02	0.656E+02	0.762E+02	0.774E+02	0.214E+03	0.0	0.258E+02	0.648E+02	0.391E+02	0.345E+02
GAS1	0.152E+02	0.198E+02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GAS1a	0.0	0.0	0.177E+02	0.120E+02	0.178E+02	0.0	0.0	0.0	0.0	0.0	0.0
STCKPL*	0.0	0.0	0.0	0.0	0.0	0.120E+02	0.332E+01	0.646E+00	0.162E+01	0.977E+00	0.863E+00
COAL1	0.180E+02	0.152E+02	0.180E+02	0.208E+02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COAL1A	0.0	0.0	0.0	0.0	0.0	0.0	0.208E+02	0.343E+02	0.459E+02	0.287E+02	0.213E+02
CLLIQU	0.0	0.0	0.100E+01	0.0	0.250E+01	0.171E+01	0.250E+01	0.151E+01	0.250E+01	0.500E+00	0.250E+01
CLTRNS*	0.960E+02	0.894E+02	0.112E+03	0.137E+03	0.0	0.0	0.0	0.224E+03	0.261E+03	0.202E+03	0.155E+03
SLPYPE*	0.128E+02	0.119E+02	0.150E+02	0.183E+02	0.0	0.0	0.0	0.747E+02	0.870E+02	0.673E+02	0.516E+02
CLPWPL	0.923E+01	0.974E+01	0.961E+01	0.824E+01	0.405E+01	0.266E+01	0.219E+01	0.0	0.0	0.0	0.0
U3O3-1	0.155E-01	0.150E-01	0.100E-01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UMILL*	0.213E+00	0.184E+00	0.250E-01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UCONV*	0.250E+00	0.216E+00	0.680E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UENRCH*	0.138E+00	0.119E+00	0.637E-01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LWRFL*	0.415E-01	0.358E-01	0.287E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L W R	0.107E+01	0.939E+00	0.533E+00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LWRRPR*	0.279E-01	0.244E-01	0.139E-01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SOLARE	0.0	0.0	0.0	0.500E+00	0.150E+01	0.350E+01	0.0	0.300E+00	0.110E+01	0.270E+01	0.270E+01
PUMPST	0.0	0.0	0.0	0.999E+00	0.314E+01	0.758E+01	0.160E+01	0.220E+01	0.388E+01	0.640E+01	0.647E+01
SOLARH	0.287E+01	0.322E+01	0.377E+01	0.394E+01	0.429E+01	0.464E+01	0.459E+01	0.468E+01	0.455E+01	0.475E+01	0.515E+01
HPWPL2	0.0	0.0	0.0	0.0	0.0	0.0	0.100E+01	0.100E+01	0.100E+01	0.100E+01	0.100E+01
ELTRNS*	0.490E+02	0.531E+02	0.560E+02	0.572E+02	0.507E+02	0.647E+02	0.780E+02	0.706E+02	0.470E+02	0.699E+02	0.475E+02
HPWPL1	0.837E+00	0.900E+00	0.975E+00	0.100E+01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GASDST*	0.297E+02	0.460E+02	0.428E+02	0.381E+02	0.387E+02	0.0	0.0	0.0	0.0	0.977E+01	0.863E+01
S2ORMV	0.0	0.0	0.500E+00	0.150E+01	0.350E+01	0.750E+01	0.155E+02	0.146E+02	0.711E+01	0.110E+02	0.110E+02

[a]Units are defined in Appendix A. Asterisk indicates endogenous variables which are evaluated in the model run.

TABLE B.3 Energy-related sectors, direct expenses (10^6 US$).

MATERIALS	1980	1981-85	1986-90	1991-95	1996- 0	2001- 5	2006-10	2011-15	2016-20	2021-25	2026-30
IR+STL	0.411E+04	0.245E+05	0.301E+05	0.306E+05	0.321E+05	0.448E+05	0.517E+05	0.373E+05	0.324E+05	0.427E+05	0.497E+05
MTLPRD	0.630E+04	0.378E+05	0.461E+05	0.502E+05	0.558E+05	0.603E+05	0.645E+05	0.647E+05	0.885E+05	0.103E+06	0.115E+06
NFERMT	0.560E+04	0.299E+05	0.330E+05	0.351E+05	0.355E+05	0.373E+05	0.453E+05	0.504E+05	0.467E+05	0.439E+05	0.489E+05
CHEMPR	0.346E+04	0.210E+05	0.257E+05	0.280E+05	0.324E+05	0.278E+05	0.257E+05	0.302E+05	0.532E+05	0.618E+05	0.685E+05
PLSTIC	0.0	0.0	0.0	0.482E+02	0.206E+03	0.523E+03	0.432E+03	0.289E+02	0.143E+03	0.396E+03	0.594E+03
PTRLPR	0.653E+03	0.472E+04	0.546E+04	0.413E+04	0.422E+04	0.482E+04	0.607E+04	0.540E+04	0.486E+04	0.613E+04	0.783E+04
HLDMTR	0.143E+04	0.865E+04	0.102E+05	0.106E+05	0.136E+05	0.210E+05	0.224E+05	0.158E+05	0.167E+05	0.218E+05	0.281E+05
LMBWOD	0.136E+04	0.739E+04	0.837E+04	0.924E+04	0.987E+04	0.104E+05	0.125E+05	0.153E+05	0.171E+05	0.178E+05	0.193E+05
MSCLMT	0.617E+03	0.328E+04	0.438E+04	0.608E+04	0.644E+04	0.669E+04	0.587E+04	0.879E+04	0.122E+05	0.138E+05	0.158E+05
EQUIPMENT											
ENGIN	0.104E+04	0.848E+04	0.105E+05	0.133E+05	0.136E+05	0.167E+05	0.168E+05	0.157E+05	0.140E+05	0.160E+05	0.201E+05
ELEQP	0.673E+04	0.369E+05	0.411E+05	0.452E+05	0.483E+05	0.521E+05	0.587E+05	0.614E+05	0.638E+05	0.651E+05	0.743E+05
MINEQP	0.152E+04	0.946E+04	0.107E+05	0.126E+05	0.142E+05	0.509E+04	0.113E+04	0.126E+05	0.448E+05	0.547E+05	0.561E+05
OILEQP	0.187E+04	0.201E+05	0.274E+05	0.126E+05	0.129E+05	0.328E+05	0.557E+05	0.341E+05	0.319E+05	0.533E+05	0.747E+05
CNSEQP	0.136E+04	0.926E+04	0.103E+05	0.101E+05	0.943E+04	0.830E+04	0.946E+04	0.135E+05	0.121E+05	0.127E+05	0.120E+05
MHNDL	0.264E+03	0.182E+04	0.197E+04	0.228E+04	0.234E+04	0.152E+04	0.164E+04	0.364E+04	0.570E+04	0.640E+04	0.585E+04
MWORK	0.687E+00	0.459E+01	0.662E+01	0.949E+01	0.103E+02	0.194E+02	0.161E+02	0.167E+02	0.177E+02	0.205E+02	0.176E+02
INSTR	0.182E+04	0.100E+05	0.113E+05	0.133E+05	0.147E+05	0.182E+05	0.200E+05	0.187E+05	0.189E+05	0.204E+05	0.240E+05
TRNEQP	0.407E+04	0.230E+05	0.270E+05	0.319E+05	0.371E+05	0.181E+05	0.552E+04	0.193E+05	0.548E+05	0.657E+05	0.720E+05
SPCEQP	0.730E+02	0.368E+03	0.395E+03	0.443E+03	0.451E+03	0.603E+03	0.608E+03	0.662E+03	0.658E+03	0.691E+03	0.630E+03
GENEQP	0.241E+04	0.143E+05	0.174E+05	0.213E+05	0.229E+05	0.208E+05	0.184E+05	0.248E+05	0.444E+05	0.508E+05	0.543E+05
PLTPRD	0.226E+04	0.177E+05	0.205E+05	0.252E+05	0.267E+05	0.347E+05	0.341E+05	0.310E+05	0.267E+05	0.287E+05	0.349E+05
MISEQP	0.205E+04	0.147E+05	0.184E+05	0.150E+05	0.149E+05	0.200E+05	0.297E+05	0.260E+05	0.250E+05	0.310E+05	0.395E+05
OTHER SECT											
TRADE	0.129E+04	0.687E+04	0.761E+04	0.839E+04	0.910E+04	0.863E+04	0.827E+04	0.880E+04	0.110E+05	0.117E+05	0.123E+05

TABLE B.4 Energy-related sectors, output (10^6 US$).

MATERIALS	1980	1981-85	1986-90	1991-95	1996- 0	2001- 5	2006-10	2011-15	2016-20	2021-25	2026-30
IRNDRE	0.600E+03	0.357E+04	0.417E+04	0.435E+04	0.473E+04	0.575E+04	0.606E+04	0.565E+04	0.643E+04	0.784E+04	0.847E+04
IR+STL	0.121E+05	0.721E+05	0.845E+05	0.879E+05	0.953E+05	0.117E+06	0.124E+06	0.114E+06	0.128E+06	0.157E+06	0.170E+06
MTLPRD	0.103E+05	0.595E+05	0.692E+05	0.753E+05	0.839E+05	0.915E+05	0.921E+05	0.994E+05	0.132E+06	0.154E+06	0.164E+06
NFERDR	0.107E+04	0.590E+04	0.655E+04	0.706E+04	0.746E+04	0.807E+04	0.885E+04	0.978E+04	0.103E+05	0.108E+05	0.116E+05
NFERMT	0.105E+05	0.580E+05	0.642E+05	0.694E+05	0.728E+05	0.788E+05	0.870E+05	0.968E+05	0.997E+05	0.103E+06	0.111E+06
CHEMPR	0.831E+04	0.489E+05	0.573E+05	0.617E+05	0.704E+05	0.684E+05	0.652E+05	0.750E+05	0.112E+06	0.131E+06	0.141E+06
PLSTIC	0.332E+04	0.186E+05	0.204E+05	0.216E+05	0.245E+05	0.268E+05	0.253E+05	0.297E+05	0.385E+05	0.451E+05	0.458E+05
PTRLPR	0.245E+04	0.151E+05	0.172E+05	0.166E+05	0.182E+05	0.197E+05	0.205E+05	0.219E+05	0.266E+05	0.315E+05	0.345E+05
HLDMTR	0.330E+04	0.182E+05	0.193E+05	0.206E+05	0.256E+05	0.361E+05	0.337E+05	0.311E+05	0.356E+05	0.437E+05	0.465E+05
LMBWOD	0.475E+04	0.267E+05	0.298E+05	0.321E+05	0.349E+05	0.388E+05	0.417E+05	0.490E+05	0.570E+05	0.633E+05	0.667E+05
MSCLMT	0.158E+05	0.930E+05	0.106E+06	0.112E+06	0.122E+06	0.138E+06	0.142E+06	0.158E+06	0.191E+06	0.223E+06	0.237E+06
TOTMT	0.724E+05	0.420E+06	0.479E+06	0.508E+06	0.560E+06	0.629E+06	0.647E+06	0.690E+06	0.837E+06	0.969E+06	0.104E+07
EQUIPMENT											
ENGIN	0.207E+04	0.147E+05	0.175E+05	0.208E+05	0.219E+05	0.250E+05	0.244E+05	0.250E+05	0.270E+05	0.316E+05	0.363E+05
ELEQP	0.113E+05	0.608E+05	0.660E+05	0.726E+05	0.788E+05	0.865E+05	0.905E+05	0.101E+06	0.109E+06	0.116E+06	0.123E+06
MINEQP	0.160E+04	0.989E+04	0.112E+05	0.132E+05	0.148E+05	0.567E+04	0.160E+04	0.133E+05	0.458E+05	0.558E+05	0.573E+05
OILEQP	0.187E+04	0.201E+05	0.274E+05	0.126E+05	0.129E+05	0.328E+05	0.557E+05	0.341E+05	0.319E+05	0.533E+05	0.747E+05
CNSEQP	0.221E+04	0.146E+05	0.168E+05	0.147E+05	0.162E+05	0.187E+05	0.161E+05	0.196E+05	0.216E+05	0.284E+05	0.233E+05
MHNDL	0.130E+04	0.734E+04	0.740E+04	0.721E+04	0.831E+04	0.954E+04	0.780E+04	0.123E+05	0.167E+05	0.204E+05	0.171E+05
MWORK	0.231E+04	0.112E+05	0.108E+05	0.113E+05	0.132E+05	0.171E+05	0.123E+05	0.182E+05	0.217E+05	0.260E+05	0.200E+05
INSTR	0.263E+04	0.142E+05	0.156E+05	0.180E+05	0.200E+05	0.246E+05	0.258E+05	0.260E+05	0.271E+05	0.297E+05	0.327E+05
TRNEQP	0.785E+04	0.435E+05	0.495E+05	0.565E+05	0.663E+05	0.438E+05	0.229E+05	0.452E+05	0.979E+05	0.118E+06	0.121E+06
SPCEQP	0.155E+04	0.679E+04	0.579E+04	0.695E+04	0.825E+04	0.880E+04	0.698E+04	0.131E+05	0.138E+05	0.153E+05	0.104E+05
GENEQP	0.472E+04	0.272E+05	0.311E+05	0.354E+05	0.389E+05	0.388E+05	0.340E+05	0.452E+05	0.715E+05	0.837E+05	0.850E+05
PLTPRD	0.393E+04	0.258E+05	0.283E+05	0.340E+05	0.369E+05	0.457E+05	0.418E+05	0.441E+05	0.433E+05	0.480E+05	0.504E+05
MISEQP	0.287E+04	0.188E+05	0.226E+05	0.194E+05	0.198E+05	0.260E+05	0.350E+05	0.329E+05	0.327E+05	0.403E+05	0.470E+05
TOTEQP	0.461E+05	0.275E+06	0.310E+06	0.323E+06	0.356E+06	0.383E+06	0.375E+06	0.430E+06	0.560E+06	0.666E+06	0.696E+06
OTHER SECT											
EXPRTI	0.197E+04	0.113E+05	0.127E+05	0.135E+05	0.150E+05	0.164E+05	0.160E+05	0.183E+05	0.234E+05	0.273E+05	0.284E+05
ENCNST	0.178E+05	0.112E+06	0.138E+06	0.159E+06	0.165E+06	0.208E+06	0.237E+06	0.227E+06	0.201E+06	0.227E+06	0.285E+06
CNSTRC	0.846E+04	0.351E+05	0.255E+05	0.305E+05	0.373E+05	0.501E+05	0.239E+05	0.623E+05	0.660E+05	0.747E+05	0.333E+05
TRNSP	0.371E+04	0.213E+05	0.238E+05	0.252E+05	0.279E+05	0.315E+05	0.312E+05	0.345E+05	0.419E+05	0.490E+05	0.508E+05
M+REPR	0.814E+03	0.470E+04	0.529E+04	0.559E+04	0.622E+04	0.687E+04	0.673E+04	0.742E+04	0.936E+04	0.110E+05	0.115E+05
TRADE	0.749E+04	0.420E+05	0.462E+05	0.494E+05	0.546E+05	0.597E+05	0.576E+05	0.664E+05	0.816E+05	0.939E+05	0.955E+05
CMUNIC	0.619E+03	0.351E+04	0.385E+04	0.411E+04	0.456E+04	0.514E+04	0.496E+04	0.572E+04	0.702E+04	0.818E+04	0.828E+04

TABLE B.5 Energy-related sectors, capacity (10^6 US$).

MATERIALS	1980	1981-85	1986-90	1991-95	1996- 0	2001- 5	2006-10	2011-15	2016-20	2021-25	2026-30
IRNORE	0.711E+02	0.256E+03	0.165E+03	0.180E+03	0.302E+03	0.518E+03	0.146E+03	0.757E+02	0.430E+03	0.533E+03	0.228E+03
IR+STL	0.147E+04	0.522E+04	0.333E+04	0.357E+04	0.616E+04	0.111E+05	0.306E+04	0.657E+03	0.867E+04	0.108E+05	0.475E+04
MTLPRD	0.105E+04	0.400E+04	0.320E+04	0.373E+04	0.450E+04	0.373E+04	0.224E+04	0.970E+04	0.776E+04	0.841E+04	0.532E+04
NFEROR	0.850E+02	0.316E+03	0.299E+03	0.295E+03	0.301E+03	0.487E+03	0.358E+03	0.508E+03	0.207E+03	0.731E+03	0.138E+03
NFERMT	0.828E+03	0.303E+04	0.296E+04	0.284E+04	0.284E+04	0.481E+04	0.394E+04	0.459E+04	0.160E+04	0.707E+04	0.122E+04
CHEMPR	0.816E+03	0.332E+04	0.257E+04	0.338E+04	0.332E+04	0.838E+03	0.129E+04	0.108E+05	0.663E+04	0.723E+04	0.492E+04
PLSTIC	0.188E+03	0.102E+04	0.789E+03	0.111E+04	0.139E+04	0.990E+03	0.253E+03	0.306E+04	0.233E+04	0.219E+04	0.125E+04
PTRLPR	0.355E+03	0.102E+04	0.664E+03	0.530E+03	0.953E+03	0.105E+04	0.571E+03	0.160E+04	0.147E+04	0.210E+04	0.103E+04
BLDMTR	0.151E+03	0.967E+03	0.777E+03	0.118E+04	0.269E+04	0.342E+04	0.0	0.0	0.217E+04	0.358E+04	0.111E+04
LMBWOD	0.425E+03	0.148E+04	0.139E+04	0.137E+04	0.187E+04	0.192E+04	0.198E+04	0.347E+04	0.265E+04	0.321E+04	0.214E+04
MSCLMT	0.193E+04	0.557E+04	0.470E+04	0.453E+04	0.746E+04	0.724E+04	0.357E+04	0.129E+05	0.105E+05	0.130E+05	0.754E+04
TOTMT	0.735E+04	0.261E+05	0.204E+05	0.231E+05	0.318E+05	0.358E+05	0.126E+05	0.515E+05	0.446E+05	0.589E+05	0.290E+05
EQUIPMENT											
ENGIN	0.750E+03	0.926E+03	0.134E+04	0.109E+04	0.109E+04	0.171E+04	0.688E+03	0.145E+04	0.859E+03	0.294E+04	0.126E+04
ELEQP	0.613E+03	0.293E+04	0.301E+04	0.354E+04	0.350E+04	0.517E+04	0.232E+04	0.606E+04	0.277E+04	0.777E+04	0.119E+04
MINEQP	0.315E+03	0.551E+03	0.697E+03	0.837E+03	0.501E+03	0.0	0.0	0.654E+04	0.356E+04	0.235E+04	0.195E+04
OILEQP	0.125E+04	0.300E+04	0.326E+04	0.0	0.0	0.704E+04	0.642E+04	0.0	0.0	0.585E+04	0.844E+04
CNSEQP	0.399E+03	0.799E+03	0.138E+04	0.0	0.709E+03	0.130E+04	0.396E+03	0.120E+04	0.982E+03	0.209E+04	0.0
MHNDL	0.475E+02	0.421E+03	0.260E+03	0.153E+03	0.453E+03	0.804E+03	0.502E+02	0.129E+04	0.123E+04	0.122E+04	0.0
MWORK	0.0	0.649E+03	0.318E+03	0.453E+03	0.913E+03	0.158E+04	0.0	0.960E+03	0.202E+04	0.163E+04	0.0
INSTR	0.153E+03	0.661E+03	0.904E+03	0.883E+03	0.139E+04	0.204E+04	0.257E+02	0.104E+04	0.851E+03	0.240E+04	0.565E+03
TRNEQP	0.438E+03	0.241E+04	0.276E+04	0.348E+04	0.304E+04	0.0	0.0	0.985E+04	0.636E+04	0.591E+04	0.377E+04
SPCEQP	0.0	0.301E+03	0.0	0.600E+03	0.316E+03	0.493E+03	0.446E+03	0.164E+04	0.281E+03	0.530E+03	0.0
GENEQP	0.412E+03	0.154E+04	0.187E+04	0.144E+04	0.222E+04	0.505E+03	0.657E+03	0.769E+04	0.437E+04	0.348E+04	0.314E+04
PLTPRD	0.106E+04	0.113E+04	0.210E+04	0.163E+04	0.313E+04	0.286E+04	0.673E+03	0.183E+04	0.799E+03	0.352E+04	0.207E+04
MISEQP	0.537E+03	0.155E+04	0.115E+04	0.0	0.929E+03	0.335E+04	0.221E+04	0.595E+03	0.124E+04	0.304E+04	0.299E+04
TOTEQP	0.564E+04	0.160E+05	0.126E+05	0.143E+05	0.190E+05	0.152E+05	0.103E+05	0.439E+05	0.317E+05	0.388E+05	0.201E+05
OTHER SECT											
EXPRTI	0.177E+03	0.660E+03	0.534E+03	0.635E+03	0.847E+03	0.576E+03	0.377E+03	0.178E+04	0.133E+04	0.142E+04	0.863E+03
ENCNST	0.435E+04	0.678E+04	0.146E+05	0.362E+04	0.133E+05	0.216E+05	0.548E+04	0.474E+04	0.408E+02	0.269E+05	0.110E+05
CNSTRC	0.0	0.186E+04	0.0	0.215E+04	0.167E+04	0.680E+04	0.0	0.632E+04	0.561E+04	0.381E+04	0.0
TRNSP	0.325E+03	0.124E+04	0.957E+03	0.117E+04	0.164E+04	0.157E+04	0.572E+03	0.271E+04	0.236E+04	0.271E+04	0.137E+04
M+REPR	0.753E+02	0.282E+03	0.211E+03	0.267E+03	0.351E+03	0.317E+03	0.131E+03	0.631E+03	0.540E+03	0.625E+03	0.318E+03
TRADE	0.543E+03	0.224E+04	0.191E+04	0.231E+04	0.299E+04	0.203E+04	0.137E+04	0.586E+04	0.444E+04	0.450E+04	0.268E+04
CMUNIC	0.472E+02	0.189E+03	0.153E+03	0.197E+03	0.268E+03	0.211E+03	0.964E+02	0.507E+03	0.391E+03	0.412E+03	0.214E+03

TABLE B.6 Capital investment (10^6 US$).

DIRECT	1980	1981-85	1986-90	1991-95	1996- 0	2001- 5	2006-10	2011-15	2016-20	2021-25	2026-30
OILINV	0.216E+04	0.207E+05	0.338E+05	0.314E+05	0.338E+05	0.590E+05	0.431E+05	0.580E+04	0.179E+05	0.624E+05	0.532E+05
GASINV	0.209E+04	0.270E+05	0.304E+05	0.0	0.0	0.328E+05	0.146E+06	0.134E+06	0.108E+06	0.137E+06	0.237E+06
CLINV	0.922E+03	0.696E+04	0.633E+04	0.745E+04	0.651E+04	0.0	0.339E+04	0.188E+05	0.294E+05	0.339E+05	0.217E+05
SYNTET	0.0	0.0	0.348E+05	0.978E+05	0.887E+05	0.903E+05	0.175E+05	0.181E+05	0.164E+05	0.145E+05	0.113E+05
FLTRNS	0.665E+04	0.401E+05	0.443E+05	0.423E+05	0.394E+05	0.413E+05	0.405E+05	0.519E+05	0.352E+05	0.419E+05	0.364E+05
PWRPL	0.946E+04	0.610E+05	0.646E+05	0.672E+05	0.645E+05	0.665E+05	0.107E+06	0.144E+06	0.106E+06	0.745E+05	0.968E+05
LWR	0.523E+03	0.238E+04	0.148E+04	0.297E+03	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FLCICL	0.583E+02	0.255E+03	0.138E+03	0.279E+02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SOLGEO	0.998E+03	0.684E+04	0.736E+04	0.144E+05	0.337E+05	0.706E+05	0.619E+05	0.167E+05	0.321E+05	0.663E+05	0.930E+05
ELTRNS	0.116E+05	0.610E+05	0.653E+05	0.681E+05	0.665E+05	0.655E+05	0.827E+05	0.930E+05	0.777E+05	0.647E+05	0.771E+05
OTHER	0.696E+04	0.373E+05	0.423E+05	0.484E+05	0.532E+05	0.616E+05	0.615E+05	0.591E+05	0.608E+05	0.627E+05	0.669E+05
TOTDIR	0.554E+05	0.355E+06	0.444E+06	0.495E+06	0.509E+06	0.654E+06	0.775E+06	0.736E+06	0.661E+06	0.776E+06	0.971E+06
CONSTC	0.414E+05	0.263E+06	0.331E+06	0.377E+06	0.386E+06	0.488E+06	0.563E+06	0.541E+06	0.483E+06	0.558E+06	0.694E+06
INDIRECT											
FERMET	0.342E+04	0.170E+05	0.107E+05	0.125E+05	0.188E+05	0.300E+05	0.378E+04	0.186E+05	0.328E+05	0.342E+05	0.134E+05
NFRMET	0.762E+03	0.366E+04	0.352E+04	0.336E+04	0.311E+04	0.543E+04	0.537E+04	0.454E+04	0.241E+04	0.809E+04	0.901E+03
BLDMTR	0.324E+03	0.107E+04	0.897E+03	0.199E+04	0.332E+04	0.378E+04	0.0	0.662E+03	0.304E+04	0.392E+04	0.109E+04
CHEMIN	0.232E+04	0.908E+04	0.554E+04	0.910E+04	0.668E+04	0.659E+04	0.646E+04	0.243E+05	0.186E+05	0.180E+05	0.111E+05
MACH	0.329E+04	0.117E+05	0.957E+04	0.953E+04	0.116E+05	0.178E+05	0.992E+04	0.240E+05	0.215E+05	0.259E+05	0.114E+05
OTHIND	0.345E+04	0.138E+05	0.104E+05	0.123E+05	0.164E+05	0.164E+05	0.127E+05	0.279E+05	0.273E+05	0.292E+05	0.156E+05
TRNSP	0.944E+03	0.386E+04	0.280E+04	0.380E+04	0.451E+04	0.494E+04	0.333E+04	0.694E+04	0.794E+04	0.779E+04	0.361E+04
BLDIND	0.708E+03	0.374E+04	0.499E+04	0.215E+04	0.563E+04	0.110E+05	0.266E+04	0.164E+04	0.461E+04	0.125E+05	0.226E+04
TOTIND	0.152E+05	0.639E+05	0.484E+05	0.547E+05	0.701E+05	0.961E+05	0.443E+05	0.109E+06	0.118E+06	0.140E+06	0.594E+05

TABLE B.7 Capital investment (10^6 US$).

DIRECT	1980	1981-85	1986-90	1991-95	1996- 0	2001- 5	2006-10	2011-15	2016-20	2021-25	2026-30
OILINV	0.522E+01	0.786E+01	0.102E+02	0.832E+01	0.874E+01	0.121E+02	0.765E+01	0.107E+01	0.369E+01	0.112E+02	0.768E+01
GASINV	0.505E+01	0.102E+02	0.919E+01	0.0	0.0	0.673E+01	0.259E+02	0.248E+02	0.223E+02	0.245E+02	0.342E+02
CLINV	0.223E+01	0.264E+01	0.191E+01	0.197E+01	0.169E+01	0.0	0.601E+00	0.348E+01	0.608E+01	0.608E+01	0.313E+01
SYNTET	0.0	0.0	0.105E+02	0.259E+02	0.230E+02	0.185E+02	0.310E+01	0.334E+01	0.340E+01	0.261E+01	0.162E+01
FLTRNS	0.160E+02	0.152E+02	0.134E+02	0.112E+02	0.102E+02	0.848E+01	0.719E+01	0.960E+01	0.728E+01	0.751E+01	0.525E+01
PWRPL	0.228E+02	0.232E+02	0.195E+02	0.178E+02	0.167E+02	0.136E+02	0.190E+02	0.265E+02	0.219E+02	0.133E+02	0.140E+02
LWR	0.126E+01	0.902E+00	0.448E+00	0.787E-01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FLCICL	0.141E+00	0.966E-01	0.416E-01	0.738E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SOLGEO	0.241E+01	0.260E+01	0.223E+01	0.381E+01	0.872E+01	0.145E+02	0.110E+02	0.309E+01	0.665E+01	0.119E+02	0.134E+02
ELTRNS	0.280E+02	0.231E+02	0.198E+02	0.180E+02	0.172E+02	0.134E+02	0.147E+02	0.172E+02	0.161E+02	0.116E+02	0.111E+02
OTHER	0.168E+02	0.142E+02	0.128E+02	0.128E+02	0.138E+02	0.126E+02	0.109E+02	0.109E+02	0.126E+02	0.113E+02	0.965E+01
TOTDIR	0.134E+03	0.135E+03	0.134E+03	0.131E+03	0.132E+03	0.134E+03	0.138E+03	0.136E+03	0.137E+03	0.139E+03	0.140E+03
CONSTC	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03
INDIRECT											
FERMET	0.224E+02	0.266E+02	0.221E+02	0.228E+02	0.268E+02	0.313E+02	0.854E+01	0.171E+02	0.277E+02	0.245E+02	0.226E+02
NFRMET	0.500E+01	0.573E+01	0.728E+01	0.613E+01	0.444E+01	0.565E+01	0.121E+02	0.418E+01	0.204E+01	0.580E+01	0.152E+01
BLDMTR	0.212E+01	0.168E+01	0.185E+01	0.364E+01	0.474E+01	0.393E+01	0.0	0.610E+00	0.257E+01	0.281E+01	0.183E+01
CHEMIN	0.152E+02	0.142E+02	0.114E+02	0.166E+02	0.954E+01	0.686E+01	0.146E+02	0.224E+02	0.157E+02	0.129E+02	0.186E+02
MACH	0.216E+02	0.182E+02	0.198E+02	0.174E+02	0.166E+02	0.185E+02	0.224E+02	0.221E+02	0.182E+02	0.186E+02	0.193E+02
OTHIND	0.226E+02	0.216E+02	0.215E+02	0.226E+02	0.235E+02	0.171E+02	0.287E+02	0.257E+02	0.231E+02	0.209E+02	0.263E+02
TRNSP	0.619E+01	0.604E+01	0.579E+01	0.693E+01	0.644E+01	0.514E+01	0.753E+01	0.639E+01	0.671E+01	0.558E+01	0.607E+01
BLDIND	0.465E+01	0.584E+01	0.103E+02	0.392E+01	0.804E+01	0.115E+02	0.602E+01	0.151E+01	0.390E+01	0.896E+01	0.381E+01
TOTIND	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03	0.100E+03

TABLE B.8 WELMM requirements (person yr/yr).

MATERIALS	1980	1981-85	1986-90	1991-95	1996- 0	2001- 5	2006-10	2011-15	2016-20	2021-25	2026-30
FERMET	0.755E+01	0.579E+02	0.755E+02	0.716E+02	0.790E+02	0.137E+03	0.136E+03	0.702E+02	0.721E+02	0.133E+03	0.144E+03
CEMENT	0.280E+01	0.266E+02	0.356E+02	0.244E+02	0.258E+02	0.309E+02	0.392E+02	0.172E+02	0.196E+02	0.335E+02	0.432E+02
COPPER	0.197E+03	0.120E+04	0.145E+04	0.207E+04	0.195E+04	0.232E+04	0.208E+04	0.192E+04	0.170E+04	0.181E+04	0.209E+04
ALUMIN	0.516E+03	0.275E+04	0.299E+04	0.325E+04	0.318E+04	0.348E+04	0.410E+04	0.416E+04	0.348E+04	0.337E+04	0.373E+04
WATER	0.192E+05	0.108E+06	0.126E+06	0.142E+06	0.157E+06	0.165E+06	0.171E+06	0.190E+06	0.220E+06	0.231E+06	0.238E+06
ENERGY(IND)											
ELPWR	0.446E+03	0.245E+04	0.266E+04	0.280E+04	0.299E+04	0.310E+04	0.317E+04	0.354E+04	0.446E+04	0.504E+04	0.537E+04
MTVPWR	0.245E+02	0.138E+03	0.152E+03	0.161E+03	0.179E+03	0.204E+03	0.197E+03	0.225E+03	0.271E+03	0.316E+03	0.319E+03
PROCHT	0.119E+04	0.689E+04	0.783E+04	0.828E+04	0.928E+04	0.104E+05	0.105E+05	0.110E+05	0.137E+05	0.161E+05	0.172E+05
W+SHT	0.436E+02	0.252E+03	0.283E+03	0.299E+03	0.329E+03	0.373E+03	0.378E+03	0.414E+03	0.500E+03	0.582E+03	0.610E+03
COAL	0.493E+03	0.290E+04	0.335E+04	0.351E+04	0.387E+04	0.456E+04	0.470E+04	0.461E+04	0.547E+04	0.655E+04	0.704E+04
GASFL	0.128E+04	0.744E+04	0.845E+04	0.894E+04	0.100E+05	0.112E+05	0.112E+05	0.119E+05	0.149E+05	0.175E+05	0.187E+05
LIQUFL	0.961E+03	0.546E+04	0.610E+04	0.651E+04	0.735E+04	0.801E+04	0.767E+04	0.870E+04	0.113E+05	0.132E+05	0.136E+05
PRTCL	0.289E+04	0.167E+05	0.190E+05	0.204E+05	0.227E+05	0.240E+05	0.830E+05	0.133E+06	0.146E+06	0.148E+06	0.147E+06
NOX	0.126E+05	0.670E+05	0.757E+05	0.853E+05	0.937E+05	0.849E+05	0.768E+05	0.812E+05	0.149E+06	0.167E+06	0.179E+06
SOX	0.722E+04	0.414E+05	0.481E+05	0.539E+05	0.615E+05	0.457E+05	0.327E+05	0.550E+05	0.159E+06	0.192E+06	0.215E+06
CO	0.802E+03	0.456E+04	0.511E+04	0.535E+04	0.587E+04	0.644E+04	0.656E+04	0.710E+04	0.824E+04	0.941E+04	0.980E+04
DEATH	0.647E+02	0.350E+03	0.389E+03	0.430E+03	0.474E+03	0.276E+03	0.150E+03	0.272E+03	0.810E+03	0.965E+03	0.108E+04
INJURY	0.332E+04	0.170E+05	0.182E+05	0.196E+05	0.206E+05	0.191E+05	0.182E+05	0.180E+05	0.228E+05	0.239E+05	0.249E+05
MANDLS	0.317E+06	0.170E+07	0.188E+07	0.207E+07	0.229E+07	0.159E+07	0.109E+07	0.173E+07	0.496E+07	0.590E+07	0.658E+07
HYDROC	0.129E+04	0.710E+04	0.766E+04	0.765E+04	0.812E+04	0.844E+04	0.855E+04	0.902E+04	0.104E+05	0.117E+05	0.124E+05

TABLE B.9 Average manpower requirements (person yr/yr).

	1980	1981-85	1986-90	1991-95	1996- 0	2001- 5	2006-10	2011-15	2016-20	2021-25	2026-30
TOTDOP	0.114E+04	0.102E+04	0.117E+04	0.134E+04	0.150E+04	0.125E+04	0.977E+03	0.104E+04	0.172E+04	0.190E+04	0.201E+04
INDOP	0.260E+04	0.249E+04	0.281E+04	0.294E+04	0.326E+04	0.366E+04	0.366E+04	0.401E+04	0.500E+04	0.589E+04	0.619E+04
DIRCNS	0.186E+03	0.232E+03	0.289E+03	0.411E+03	0.380E+03	0.425E+03	0.372E+03	0.419E+03	0.349E+03	0.315E+03	0.370E+03
INDCNS	0.423E+02	0.289E+02	0.209E+02	0.251E+02	0.307E+02	0.412E+02	0.197E+02	0.512E+02	0.542E+02	0.614E+02	0.274E+02

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THE DYNAMICS OF ENERGY SYSTEMS AND THE LOGISTIC SUBSTITUTION MODEL

C. Marchetti and N. Nakicenovic

PREFACE

One of the objectives of IIASA's Energy Systems Program is to improve the methodology of medium- and long-range forecasting in the areas of the energy market and energy use, demands, supply opportunities and constraints. This is commonly accomplished with models that capture and put into equations the numerous relationships and feedbacks characterizing the operation of an economic system or parts of it. Such an approach encounters many difficulties, which are linked to the extreme complexity of the system and the fairly short-term variation of the parameters and even of the equations used. Consequently, these models lend themselves to short- and perhaps medium-range predictions, but normally fail to be useful for predictions over a period of about 50 years, the time horizon that the Energy Systems Program has chosen for study.

Following the current scheme of attacking similar problems in the physical sciences, we have left aside all details and interactions, and have attempted a macroscopic description of the system via the discovery of long-term invariants. Heuristically, this approach is certainly not new. In a broad sense, the sciences can be seen as a systematic search for invariants.

This work is dedicated to the empirical testing and theoretical formulation of an invariant, the logistic learning curve, as it applies to the structural evolution of energy systems and systems related to energy, such as coal mining. The great success of the model in organizing past data, and the insensitivity to major political and economic perturbations of the structures obtained seem to lend great predictive power to this invariant.

This Research Report represents only part of the work done at the International Institute for Applied Systems Analysis, under a grant from the Volkswagenwerk Foundation, FRG, on the potential of logistic analysis in describing energy systems. It is completely documented in the Administrative Report to the foundation entitled "The Dynamics of Energy Systems and the Logistic Substitution Model" (Marchetti *et al.* 1978).

The present paper reproduces the descriptive part in Section B of the Administrative Report. The software is described by Nakicenovic (1979). As for the theoretical treatment in Section C by Peterka, a new issue of "Macrodynamics of Technological Change: Market Penetration by New Technologies" is available (Peterka 1977). Fleck's contribution to Section C on the regularity of market penetration is part of his forthcoming doctoral dissertation at the University of Karlsruhe. Section A of the Administrative Report is the executive summary.

SUMMARY

Information, material, and energy are the basic constituents of civilization, and it is most natural that we should try to assess their respective roles and internal mechanisms. The question of energy has been enjoying much attention lately, partly because of the very successful move by the oil cartel in 1973. The political consequences and the promotional infrastructure of that move have generated a highly emotional atmosphere, inimical to an objective appreciation of the facts. In this study in IIASA's Energy Systems Program, we have attempted to leave aside emotions and *ad hoc* interpretations. Sticking only to the facts, we have tried to find out if they have an internal order of their own, or, in the terminology of physics, if they can be described phenomenologically. We find that this is possible.

Our initial working hypothesis was that primary energies, such as wood, coal, oil, gas, and nuclear energy, are just technologies competing for a market. Consequently, market penetration analysis, as it has been developed by Mansfield (1961) and many others, should be applicable. In order to test the power and the limits of this analysis, we worked on as many examples as could be used, on three different levels of aggregation:

Primary energy inputs for the world as a whole
Primary energy inputs for individual nations or clusters of nations
Energy subsystems, such as electric utilities

A total of about 300 cases were examined. Since the goodness of fit was consistently high, the examples in this report have been chosen for mainly didactic reasons. The United States is particularly well represented, largely because of the quality and detail of U.S. statistics. A good repre-

sentation of FRG data was also attempted. Since supertankers have made the energy system a world system, the case of the world as a whole was given special attention for its political and resource implications. Although the main thrust of our analysis has been to provide a simple, objective, and internally consistent description of the past, we made a projection of the future, as it is described by the equations, and commented on it. But given that our projections are often different from what one has come to expect according to current wisdom, our attempt has to be considered exploratory. After all, it is perfectly legitimate in scientific research to test the limits of a newly discovered tool by extending its range of application beyond its "natural" bounds.

There is another important point to be mentioned, regarding possible control of the process of substitution of one technology for another. No technology can start from zero without external financial help. The magnitude of the initial external investment determines the initial conditions for the substitution, and may considerably accelerate the substitution process (or delay it, if the investment is too small), especially if the new technology is profitable but requires high investments. The example of nuclear energy is treated in some detail.

On the whole, we believe that the basic objective of this work has been fulfilled: we explored the field experimentally, showing the great efficiency of our model in organizing data. In doing so, we have presumably generated more problems than we have solved, which is a good indication that we have been plowing a fertile field.

1 INTRODUCTION

Four years ago, the International Institute for Applied Systems Analysis began a study of energy systems using the techniques of market penetration analysis. The basic hypothesis – which has proved very fruitful and powerful – is that *primary energies, secondary energies, and energy distribution systems are just different technologies competing for a market* and should behave accordingly.

Previous analysis of market competition had always been performed for only two competitors. But it is a peculiarity of energy systems over the last hundred years that most of the time more than two competitors took important shares of the market. Thus, we had to modify the original rules by introducing new constraints that permitted us to deal with more complicated cases. These constraints were defined empirically from a few cases, but proved very successful in dealing with virtually all the cases that we analyzed. A mathematical formulation of the substitution process is given below and the manual for the software package is given in Nakicenovic (1979).

2 THE LOGISTIC FUNCTION AND SUBSTITUTION DYNAMICS

Substitution of a new way for the old way of satisfying a given need has been the subject of a large number of studies. One general finding is that almost all binary substitution processes, expressed in fractional terms, follow characteristic S-shaped curves, which have been used for forecasting further competition between the two alternative technologies or products, and also the final takeover by the new competitor.

Most of the studies of technological substitution are based on the use of the logistic function. The logistic function, however, is not the only S-shaped function, but it is perhaps the most suitable one for empirical analysis of growth and substitution processes because of both the ease in interpreting the meaning of its parameters and the simplicity in estimating the parameters from the observed phenomena. Another S-shaped function, the Compertz curve, has also been frequently used, especially to describe population, plant, and animal growth (see, e.g., Richards 1959).

The widespread empirical applications of the logistic function as a means of describing growth phenomena also originated in the studies of human population, biology, and chemistry. The first reference to the logistic function can be found in Verhulst (1838, 1845, 1847). Pearl (1924, 1925) rediscovered the function and used it extensively to describe the growth of populations, including human population. From then on, numerous studies have been conducted only to confirm the logistic property of most growth processes. Robertson (1923) was the first to use the function to describe the growth process in a single organism or individual. Later, the function found application in work concerning bioassays (see e.g., Emmens 1941, Wilson and Worcester 1942, and Bergson 1944), and in work on the growth of bacterial cultures in a feeding solution, autocatalyzed chemical reactions, and so on.

One of the first studies that showed that technological substitution can be described by an S-shaped curve was the pioneering work of Griliches (1957) on the diffusion of the hybrid corn seed in the United States. He showed that hybrid corn replaced traditional corn seed in different states in a very similar way; the S-shaped substitution was only displaced in time by a few years and lasted differing lengths of time from one state to another.

Following the work of Griliches, Mansfield (1961) developed a model to explain the rate at which firms follow an innovator. He hypothesized that the adoption of an innovation is positively related to the profitability of employing the innovation and negatively related to the expected investments associated with this introduction. Mansfield substantiated the theoretical implications of his model by the empirical analysis of the diffusion of 12 industrial innovations in four major industries.

One of the most notable models of binary technological substitution, which extended Mansfield's findings, was formulated by Fisher and Pry (1970). This model uses the two-parameter logistic function to describe the substitution process. The basic assumption postulated by Fisher and Pry is that once a substitution of the new for the old has progressed as far as a few percent, it will proceed to completion along a logistic substitution curve:

$$\frac{f}{1-f} = \exp(\alpha t + \beta)$$

where t is the independent variable usually representing some unit of time, α and β are constants, f is the fractional market share of the new competitor, and $1 - f$ that of the old one. *The coefficients α and β are sufficient to describe the whole substitution process.* They cannot be directly observed; they can, however, be estimated from the historical data.

Two sets of examples are shown here (Figures 1 and 2) from the original papers of Fisher and Pry (Fisher and Pry 1970, Pry 1973). The logistic functions appear to give an excellent description of substitution, not only for very different products and technologies, but also for different types of economies.

In dealing with more than two competing technologies, we have had to generalize the Fisher–Pry model since in such cases logistic substitution cannot be preserved in all phases of the substitution process. Every given technology undergoes three distinct substitution phases: growth, saturation, and decline. The growth phase is similar to the Fisher–Pry binary logistic substitution, but it usually terminates before full substitution is reached. It is followed by the saturation phase which is not logistic, but which encompasses the slowing of growth and the beginning of decline. After the saturation phase of a technology, its market share proceeds to decline logistically.

We assume that only one technology is in the saturation phase at any given time, that declining technologies fade away steadily at logistic rates uninfluenced by competition from new technologies, and that new technologies enter the market and grow at logistic rates. The current saturating technology is then left with the residual market share and is forced to follow a nonlogistic path that joins its period of growth to its subsequent period of decline. After the current saturating technology has reached a logistic rate of decline, the next oldest technology enters its saturation

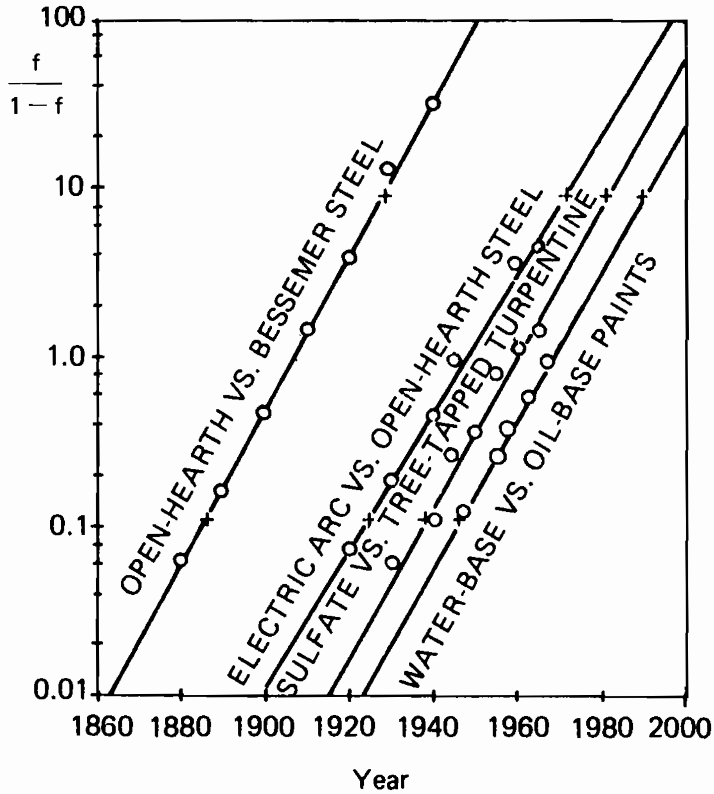


FIGURE 1 Technological substitution in the production of steel, turpentine, and paints. Source: Fisher and Pry (1970).

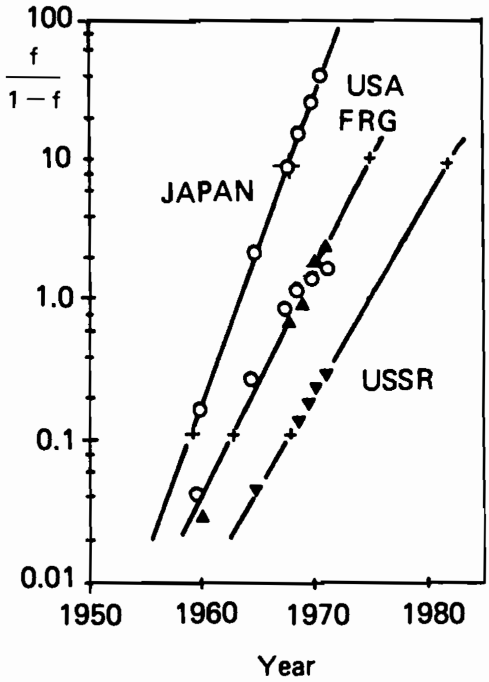


FIGURE 2 Substitution of the basic oxygen furnace for open-hearth and Bessemer steel production. On the line in the middle, the triangles represent the FRG and the circles represent the USA. Source: Pry (1973).

phase and the process is repeated until all but the most recent technology are in decline. In effect, our model assumes that technologies that have already entered their period of market phaseout are not influenced by the introduction of new ones. Deadly competition exists between the saturating technology and all other technologies.

3 A SIMPLIFIED ANALYTICAL TREATMENT

Let us assume that there are n competing technologies ordered chronologically in the sequence of their appearance in the market, technology 1 being the oldest and technology n the youngest. Over a certain historical interval we estimate the coefficients of the logistic functions for the technologies in the logistic substitution phases. Typical historical periods we have investigated range from 130 to 20 years. The substitution process can be simulated, however, over any desired time interval which need not overlap with the historical period. Let us call the beginning of this interval t_B and the end t_E.

After the coefficients have been estimated, either by ordinary least squares or by some other method, we have n equations:

$$f_i(t) = 1/[1 + \exp(-\alpha_i t - \beta_i)]$$

where $i = 1, \ldots, n$ and where α_i and β_i are the estimated coefficients. Now we identify the saturating technology, j, as the oldest technology still increasing its market share. The market shares are then defined by:

$$f_i(t) = 1/[1 + \exp(-\alpha_i t - \beta_i)] \qquad \text{for } i \neq j$$

For j they are defined by

$$f_j(t) = 1 - \sum_{i \neq j} f_i(t)$$

At this time, technology j is in its saturation phase and all other technologies are either growing or declining logistically.

Now we need a criterion to identify the end of the saturation phase and the beginning of the decline of technology j, at which time the function $f_j(t)$ will become logistic again on its way down and the burdens of saturation will fall on technology $j + 1$. To establish this criterion, we use the properties of the function

$$y_j(t) = \log \frac{f_j(t)}{1 - f_j(t)}$$

If $f_j(t)$ were logistic, $y_j(t)$ would be linear in t. However, for $f_j(t)$ in its saturation stage, the function $y_i(t)$ has negative curvature, passes through a maximum where technology j has its greatest market penetration, and then decreases. The curvature diminishes for a time, indicating that $f_j(t)$ is approaching the logistic form, but then, unless technology j is shifted into its period of decline, the curvature can begin to increase as newer technologies enter the market place. Phenomenological evidence from a number of substitutions suggests that the end of the saturation phase should be identified with the time when the ratio of the curvature of $y_j(t)$ to its slope reaches its minimum value. We take this criterion as the final constraint in our generalization of the substitution model, and from it we determine the parameters for technology j in its logistic decline.

In mathematical form, the criterion for termination of the saturation phase for technology j is

$$y_j''(t)/y_j'(t) = \text{minimum}$$

(note that y'' and y' are both negative in the region of the minimum). When the minimum condition is satisfied, we call this time point t_{j+1}, the time of the beginning of saturation for technology $j + 1$, and determine coefficients α and β for the declining phase of technology j from the relationships

$$\alpha_j = y_j'(t_{j+1})$$

$$\beta_j = y_j(t_{j+1}) - \alpha_j t_{j+1}$$

Then the next-oldest technology $j + 1$ enters its saturation phase, and the process is repeated until the last technology n enters its saturation phase, or the end of the time period t_E is encountered.

These expressions determine the temporal relationships between the competing technologies. Only time t and the estimated coefficients α_i and β_i extracted from historical data have been treated as independent variables.

4 COMMENTS AND WARNINGS ON USING THE CHARTS FOR PREDICTION

Logistic analysis has shown an unexpected capacity to organize historical data, in that the information relevant to the evolutionary behavior of energy systems is contained in very restricted time series. This provides a very sound basis for using it for prediction. However, a certain number of precautions should be taken, or at least kept in mind when using the results.

First of all, a new primary energy, like any new technology, is introduced first by drawing capital and resources from the industrial and economic environment. This "investment in faith" usually shows up with very fast rates of market penetration right at the beginning followed by a reflection period, after which speed is resumed in compliance with the market. As a new technology, now a new industry, has to walk on its own legs, its speed of penetration is always lower. This transition point, or kink in the curve, usually occurs by the time penetration has reached 2 or 3 percent of the market. If this kink does not show up, one is left with the suspicion that it will occur later, so that the final rate of penetration has to be guessed from other indicators. The most useful indicator is the time constant prevalent for other substitutions in the same system, and this is what we often use for our scenarios.

In the energy field, natural gas has the tendency to keep the boosted track up to even 10 percent of market penetration. This behavior merits further study as it may permit a better insight into the introduction period of a new technology. One of the possible explanations is that at the beginning, natural gas can fill an existing distribution infrastructure so that only trunk transportation has to be provided during the initial phase.

Secondly, the model does not predict the introduction of a new technology. This limits the time horizon of forecasting. Analysis of numerous cases has shown that each system has a fairly stable time constant. For example, the time constant (time to go from 1 to 50 percent of the market share) for the introduction of a new energy source in the world is about 100 years. Consequently, from the point of view of the competitors, not very much is going to happen during the first 50 years of the introduction of a new technology. This offers much breathing space when we discuss the world. But prudence is advisable when we deal with a time constant of only 20 or 30 years, as we find for the FRG.

The weakest point for the predictions over the next 50 years is the role of nuclear energy; we have a starting point for the curve, but we still cannot determine the slope. For that reason, we intentionally took prudent values, e.g., a penetration of only 6 percent for the world in the year 2000, backed by a slightly more optimistic value of 10 percent. At these levels of nuclear energy penetration, it is clear that the predictions of the future roles of the various sources of energy based on this model contradict most of the predictions in the current literature, which are mainly controlled by the much looser constraints of resource availability and political opportunity.

The causal importance of resource availability is weakened by the fact that oil successfully penetrated the energy market when coal still had an enormous potential, just as coal had previously penetrated the market when wood still had an enormous potential. The causal importance of the political argument is weakened by the smooth substitution observed over a period of more than a century, when political moods changed quite frequently and drastically. Furthermore, the drastic changes in energy prices after 1973, even if of monopolistic origin, do not appear a sufficient cause to change the rates of substitution; similar price changes in the past did not affect them either. This has been so at least for the medium- and long-run, presumably because of rapid relative price re-adjustments between various energy sources. While this is only a hypothesis, which merits a deeper study, the very rapid price adjustments after recent oil price increases are well in tune with it.

The most important predictions of our model that differ from those in the current literature are that there will be

A relatively rapid phaseout of coal as a primary energy source
A quite important role for natural gas in the next 50 years

A negligible role in the next 50 years for new sources such as geothermal energy, solar energy, and fusion because of the very long lead times *intrinsic* to the system

The curious fact about the last point is that the flourish of very expensive research on these sources implies a fairly low discounting factor in decisions on the allocation of funds for energy R&D. This appears to be very wise, if not internally consistent, because the lead times of the systems are so long that nothing could be started rationally if higher discounting rates were used.

These and many other predictions (like the compatibility of resources with demand), although extremely interesting, are not really part of our research task; our work is centered in the past, where we try to find order and which we try to understand rationally.

5 THE EXAMPLES

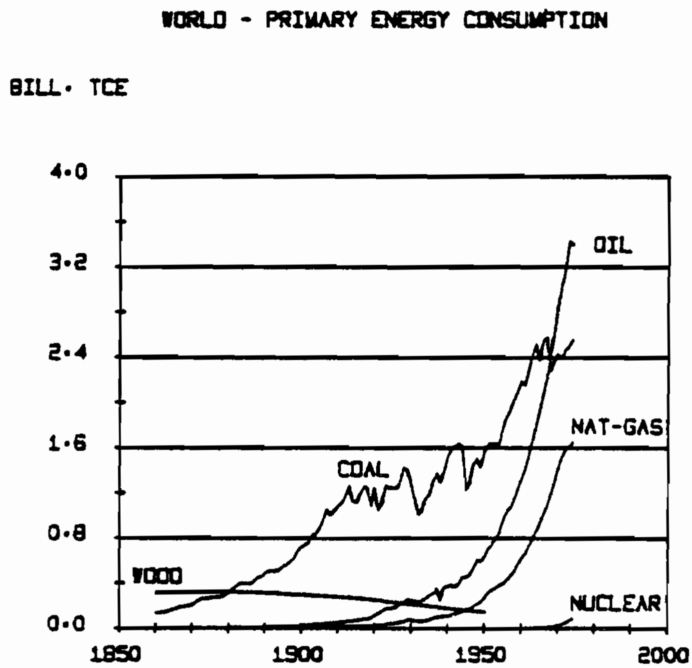
The aim of the experimental part is to show the scope and power of the method by taking as many examples as possible from three different levels of aggregation:

Primary energy inputs for the world as a whole
Primary energy inputs for single nations or a cluster of nations
Energy subsystems, such as electric utilities

In total, we used 60 data bases to generate 300 examples for 30 different spatial and structural subsets of the world energy system. The goodness of fit was consistently high in all examples, so the cases reported here have *been chosen mainly for didactic reasons.*

The United States is particularly well represented, largely because of the quality and detail of its statistics. We also made an effort to have a good representation for the Federal Republic of Germany. If this research should be continued, collaboration with an institute for statistics would have a multiplicative effect on the results.

To make the curves easy to interpret, the substitution graphs are drawn using the transformation $\log[f/(1-f)]$ versus time (f being the market share). This makes the top and bottom part of the graph very sensitive and this fact should be kept in mind when drawing conclusions only from an examination of the graphs. The graphs showing total energy consumption are drawn on either logarithmic or linear axes, or on both, depending on the dispersion of the data.

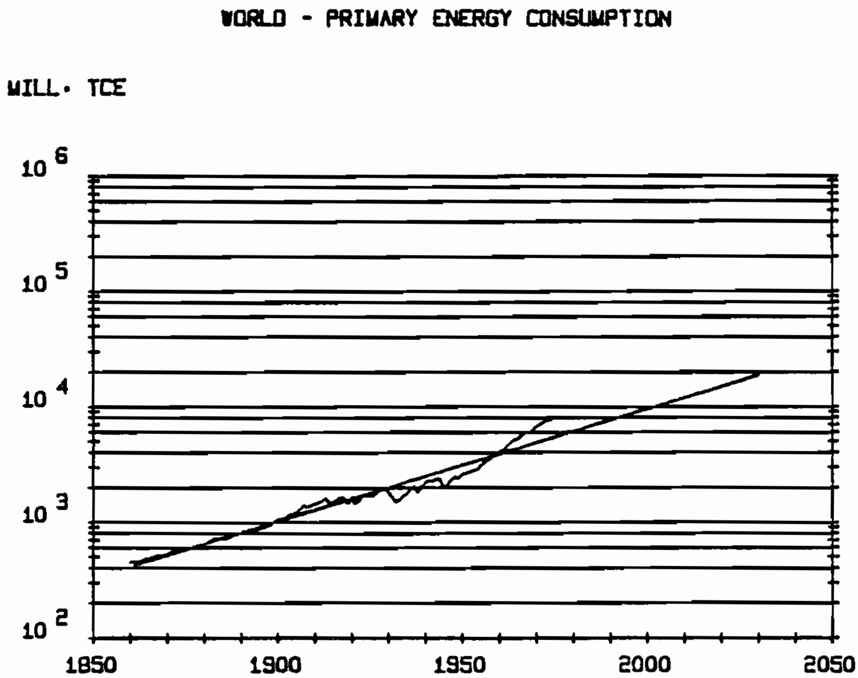


World energy consumption is reported first in various forms to illustrate and clarify our methods of logistic analysis. Our world statistical data base includes wood, coal, oil, natural gas, and nuclear energy as the major energy sources of history.

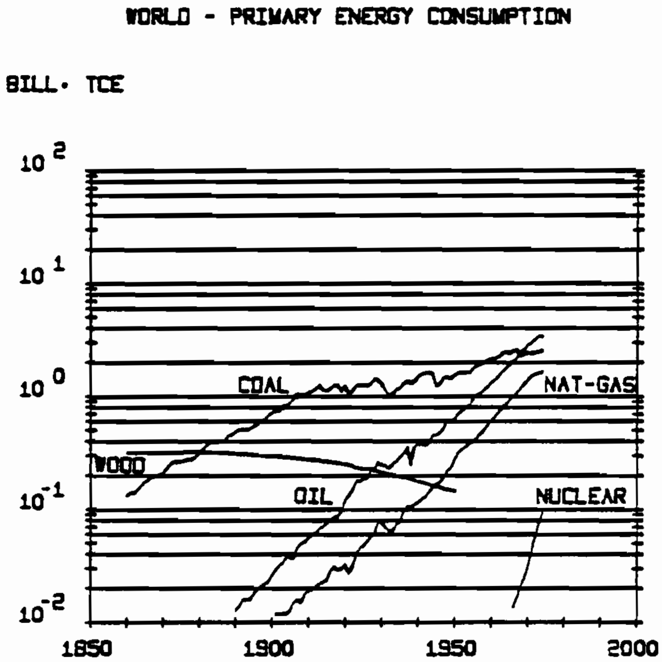
Historical data on the consumption of coal, oil, natural gas, and nuclear energy from 1860 to 1974 were taken from Schilling and Hildebrandt (1977), and data on fuel wood consumption were taken from Putnam (1953). Although fuel wood consumption levels for the years 1950 to 1974 were not available, during this period the use of fuel wood was not very large so that any error thus introduced is not significant. All energy sources have been expressed in terms of their energy content in tons of coal equivalent (tce); 1 tce equals 7 million kcal.

Nuclear energy was not available directly as primary equivalent but in gigawatt hours of electricity (GWh(e)). We have converted nuclear electric energy into tce of nuclear energy on the basis of an overall thermal-to-electric conversion rate of 33 percent.

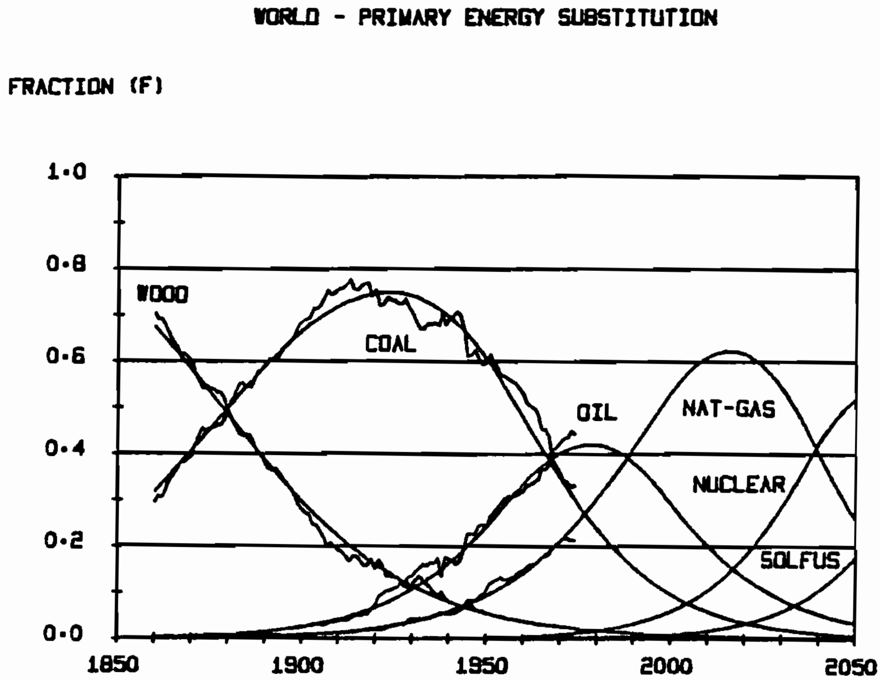
The energy inputs for the world are plotted here in billions of tce according to primary energy form. Many features related to economic or political events appear in the figure, but no consistent patterns are visible. Initial growth of new sources appears to be exponential. The smoothness of the line for wood raises suspicion and points to artificial estimation methods used to generate the original wood consumption time series.



When wood is included with the commercial energy sources, the development of world energy consumption appears fairly regular until World War II, with a growth of 2.2 percent per year. After 1950, not only were the losses reabsorbed that occurred as a consequence of the great recession, but some overshooting occurred with respect to the trend line. This may have been caused by an increase in the rate of population growth after the war. The increase in energy costs may well temper this rate again.

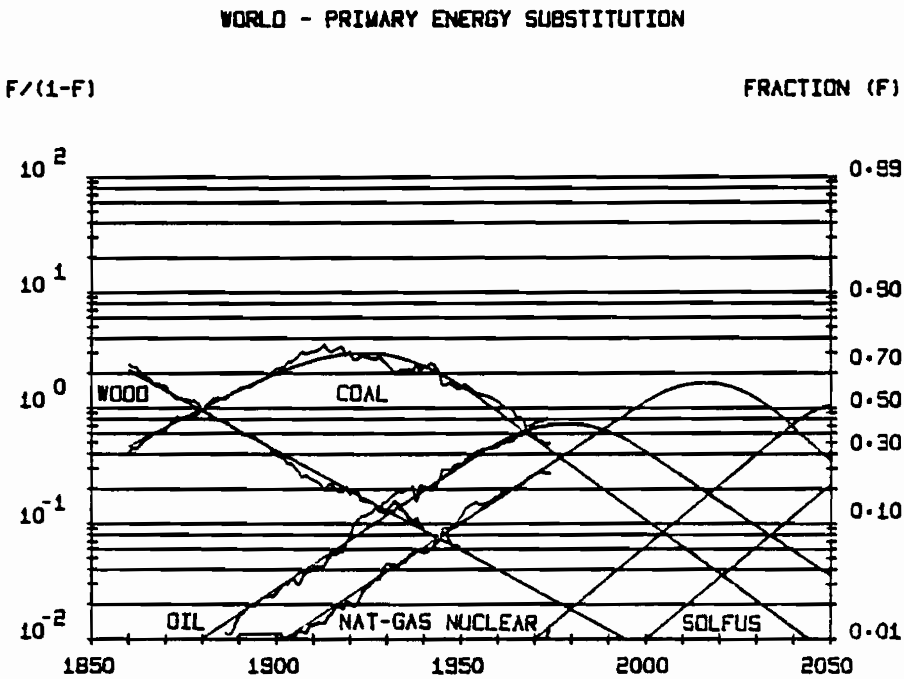


New sources appear to grow with exponential trends. Therefore, we plotted them in semilogarithmic form. The presence of some straight lines indicates that we are moving in the right direction, but we still do not find consistent general trends allowing a precise mathematical description of the evolution of the use of the various primary energy sources.



Here the contributions of the various primary sources are shown as fractions of the total market. The smooth curves are two-parameter logistics assembled in a system of equations as described in the text. *The fitting appears perfect for historical data.*

When we look to the future, the figure contains two primary energy sources for which a complete fitting of the parameters was not possible. For nuclear energy the present penetration is still too low to determine the slope of the penetration. We have estimated the rate from progress to date and from official plans. For SOLar or FUSion, the scenario is completely hypothetical. Because rates of penetration were almost the same for coal, oil, and gas, we assumed an equal rate for nuclear and SOLFUS, in the spirit of "business as usual." The unexpected dominance of natural gas over the next 50 years will be discussed later in the report.


WORLD - PRIMARY ENERGY SUBSTITUTION
F/(1-F)
FRACTION (F)
10 2
10 1
10 0
10-1
10-2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
WOOD
COAL
OIL
NAT-GAS
NUCLEAR
SOLFUS
1850
1900
1950
2000
2050

The curves of the preceding figure are now plotted as $\log[f/(1-f)]$; the logistic curves appear as straight lines, greatly helping visual inspection and formal considerations. The first fact to be observed is the *extreme regularity and slowness* of the substitution. It takes about 100 years to go from 1 percent to 50 percent of the market. We call this length of time the *time constant* of the system.

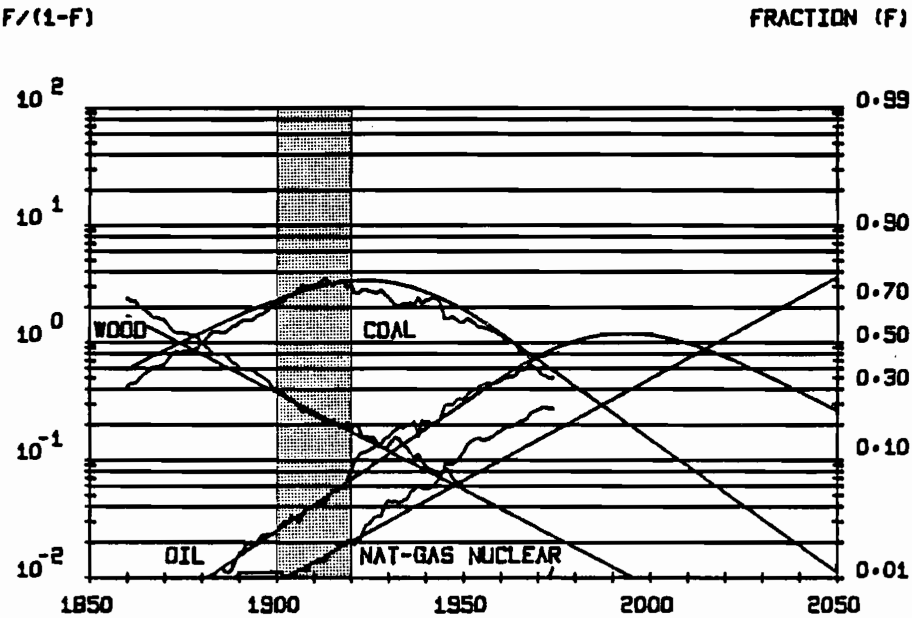
The regularity refers not only to the fact that the rate of penetration (defined as constant α in the equation and corresponding to the slope of the curves) remains constant over such very long periods when so many perturbing processes seem to take place, but also to the fact that all perturbations are reabsorbed elastically without influencing the trend. It is as though *the system had a schedule, a will, and a clock.*

It is also interesting to note that no source finally saturates the market, although nuclear may do so if it is not followed by something else. The dynamics of the introduction of new sources and the high time constant lead to maximum penetrations of 60 to 70 percent. This is also true for most smaller systems, as will be shown later.

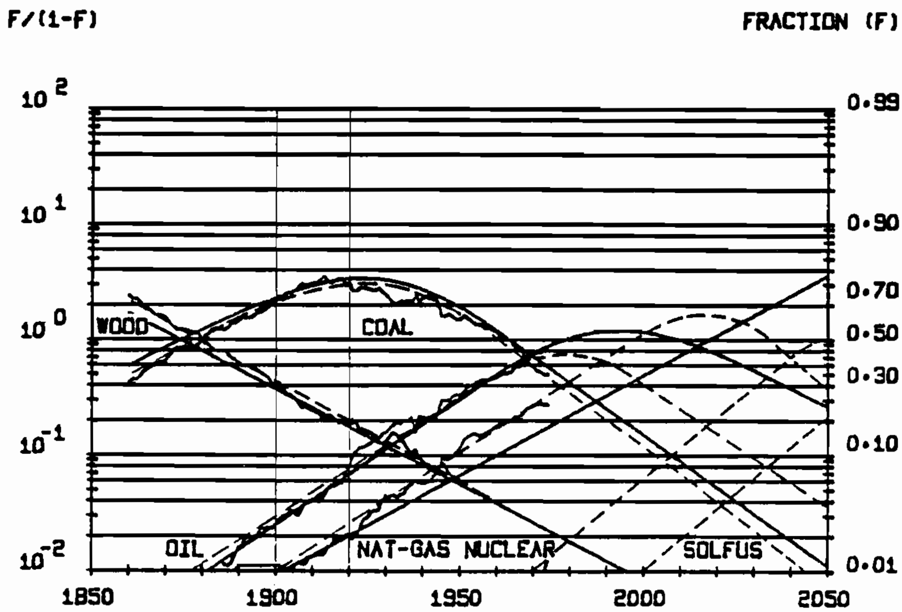
Nuclear achieved only a 1-percent share of primary energy in the early 1970s; thus its future penetration rate cannot be distilled from the historical data. In 1977, installed nuclear capacity reached 88 GW(e) (IAEA 1977). Taking an overall utilization factor of 75 percent, the nuclear share in primary energy consumption is about 2 percent.

By 1990, according to the IAEA (1977), power plants currently under construction and planned should be in service; thus, the total installed capacity should be at least 430 GW(e). With a rough utilization factor of 75 percent, this corresponds to a 5- to 10-percent share in 1990, depending on whether we use a 2-percent or a 3-percent growth rate of primary energy during the next 12 years. We have chosen a more modest nuclear share to account for possible delays in the construction of the planned power plants: our nuclear scenario prescribes a 6-percent nuclear share in the year 2000. Note that the introduction of SOLFUS in the year 2000 would not influence nuclear until around 2050.

WORLD - PRIMARY ENERGY SUBSTITUTION (SHORT DATA)



WORLD - PRIMARY ENERGY SUBSTITUTION (SHORT DATA)



As available statistics are sometimes unreliable, have gaps lasting for long periods of time, or refer to certain energy sources and not to others, we have tried to check the stability of the fitted functions and of the forecasts with respect to restrictions in the information base. The results are very encouraging, showing that the relevant information can be extracted from relatively short data swaths.

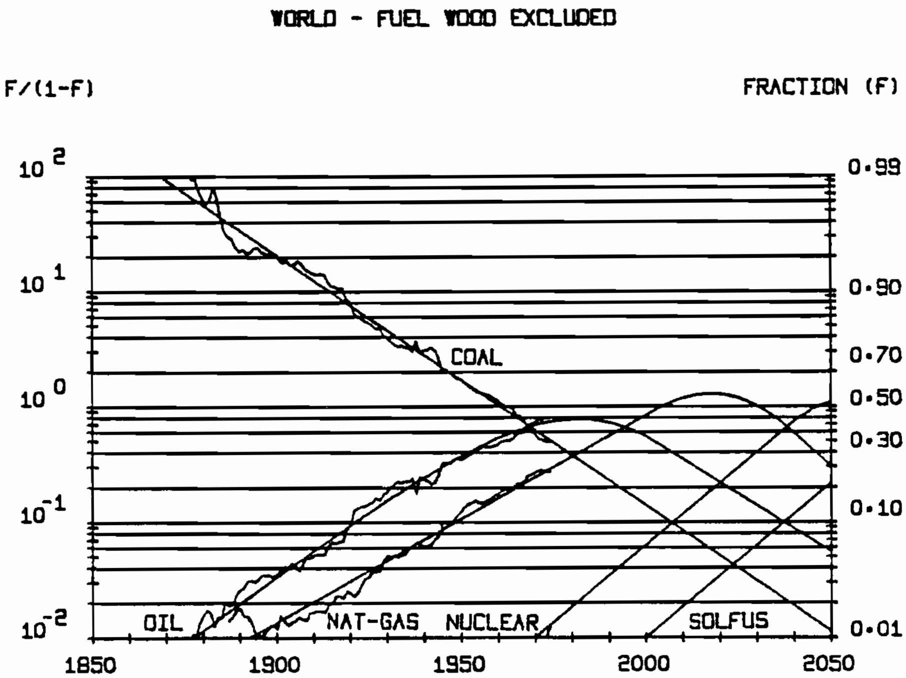
Each curve in our system can be fitted with only two points, since only two points are needed to define a straight line. Consequently, the large number of statistical data serve only to reduce noise. However, 20 years of data already constitute an excellent base. We have tried, then, to reconstruct all the periods under examination, using only a time series of 20 years, between 1900 and 1920. This base has the disadvantage that gas has reached only a 2-percent share and consequently its long-term substitution rate may not yet be established.

The smooth curves fitted to the 1900–1920 data still show an extraordinary agreement with the data outside the historical period. Natural gas deviates somewhat and there is an error in the "prediction" of about 7 percentage points at the end of the period. This may seem relatively large, but it is a prediction made 50 years ahead from a small market share, and with a depression and a war in between!

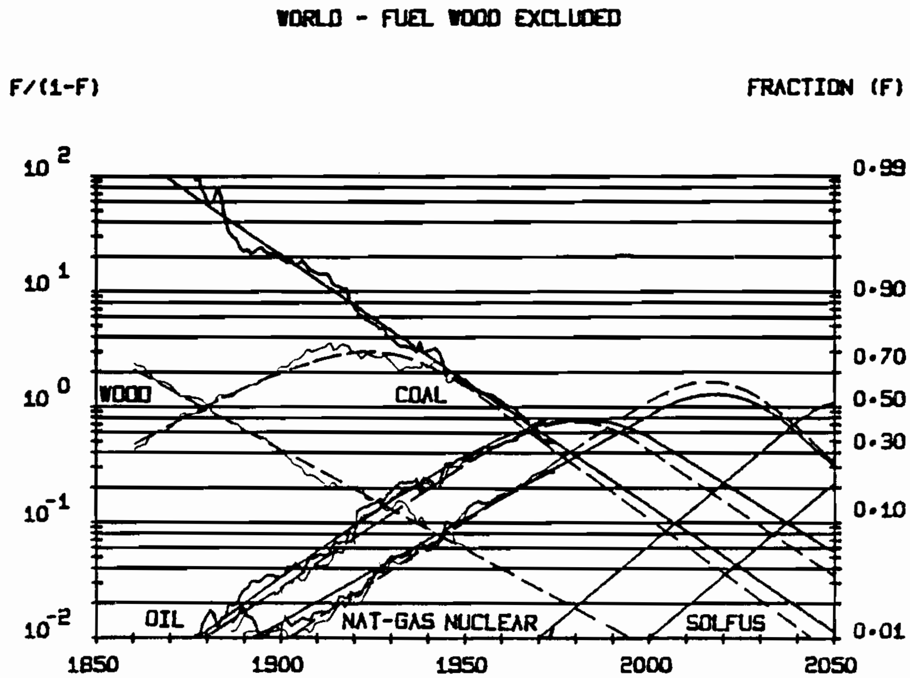
Because the model does not predict the introduction of new primary energy sources, nuclear does not appear at all in these projections. Yet the absence of nuclear was of no consequence for the 50 years from 1920 to 1970, and, as shown in the previous figure, nuclear will be of little consequence for the other energy sources until it penetrates 5–10 percent of the market in about 2000.

These observations are of the greatest importance since they give logical support to the use of our system of equations for projections into the future. In the lower figure, superposing the curves fitted on a short data base with those fitted on the complete data base shows the relatively small differences. Additionally, whenever the timing and penetration rates of future technologies must be estimated, as for nuclear and SOLFUS, the system of equations serves to establish internal consistency for each scenario.

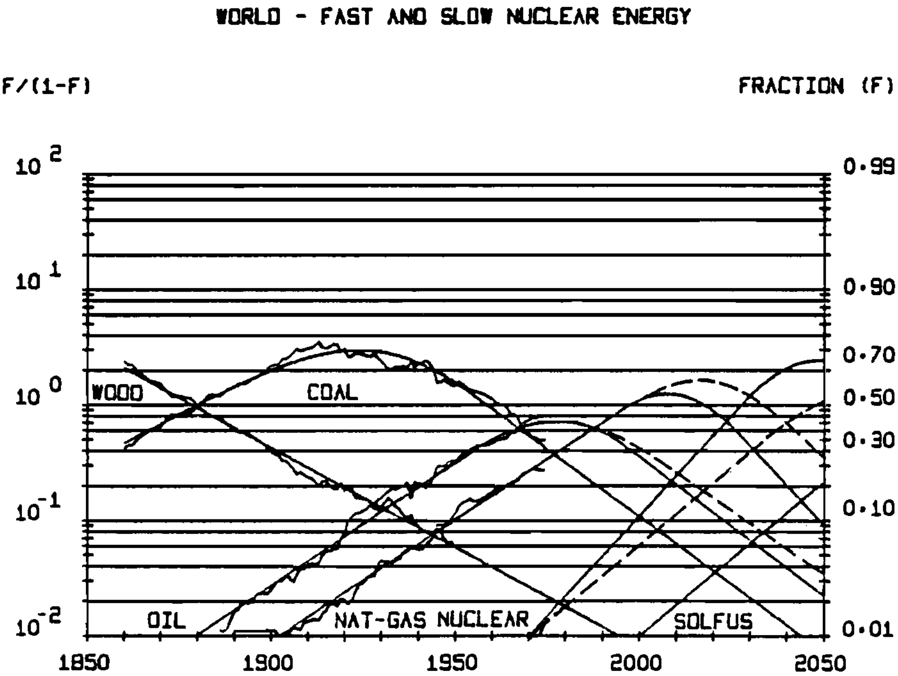
Superposition of the curves calculated with the short data base (solid lines) and the extended data base (dashed lines) shows the remarkable predictive ability of the short data base over a period of half a century, and illustrates the gradual accumulation of errors.



This experiment shows that much information about the total system can be extracted from a structural subset. From the complete data base, we had the impression that wood statistics were too smooth to be accurate, and in a certain measure represent educated guesses of the statistical offices. Consequently, we omitted wood and analyzed the competitive behavior of the other primary sources left in the market. As the figure shows, the logistic description fits the subset perfectly. In the following figure, the curves with and without wood are superposed, to show that little information is lost when wood statistics are eliminated.



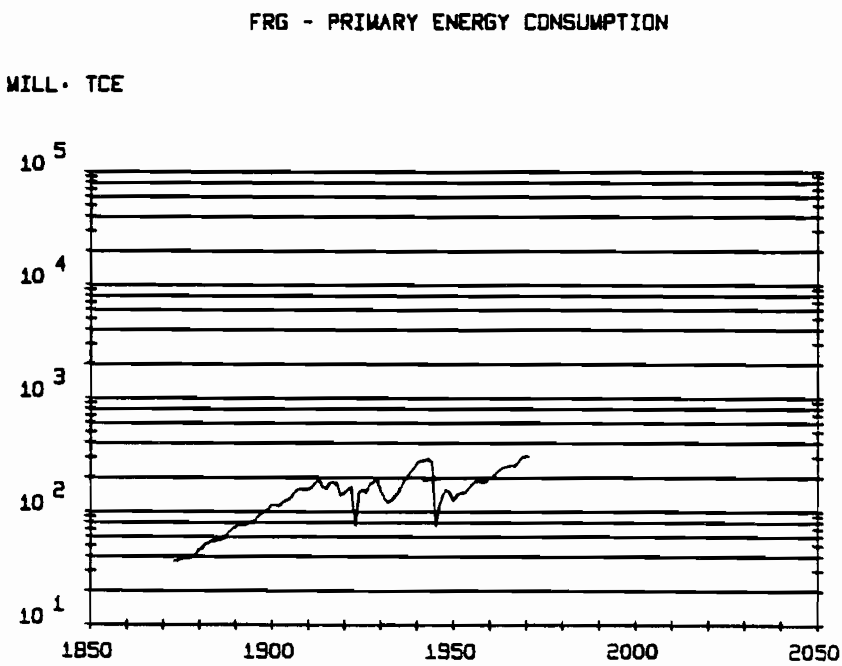
To better appreciate the level of the errors made by eliminating fuel wood data, we superposed the two sets of curves. The differences never went beyond a few percent of the market, showing that key information about the dynamics of the market is contained in and can be extracted from restricted subsets of the original data base.


WORLD - FAST AND SLOW NUCLEAR ENERGY
F/(1-F)
FRACTION (F)
10 2
10 1
10 0
10-1
10-2
0·99
0·90
0·70
0·50
0·30
0·10
0·01
WOOD
COAL
OIL
NAT-GAS NUCLEAR
SOLFUS
1850
1900
1950
2000
2050

The history of nuclear energy is too short and the market penetration of nuclear energy is too small to provide a reliable indication of the long-term market penetration rate. We made a sensitivity analysis to explore the consequences of this uncertainty. A plot with a nuclear energy share of 6 percent in the year 2000 and one with a 10-percent share in the year 2000, almost doubling the rate, are superposed.

This figure reveals very interesting properties of the logistic competition. Primary fuels on their way down are insensitive to a change in the rate of newcomers. After the great fuss about nuclear energy tramping into the garden of coal, and coal being reshaped as a tool to stamp out nuclear, this appears very refreshing, if unexpected.

Nuclear appears to interact strongly only with natural gas, presumably preempting the markets into which it could have expanded, and interacts only marginally with oil, which may disappoint those who install nuclear power stations to reduce their need for oil imports. The problem of resource availability that automatically comes to mind is not dealt with here. It appears, however, that the substitution mechanism itself takes care of it. Actually, leftovers seem a stable characteristic of the operation.

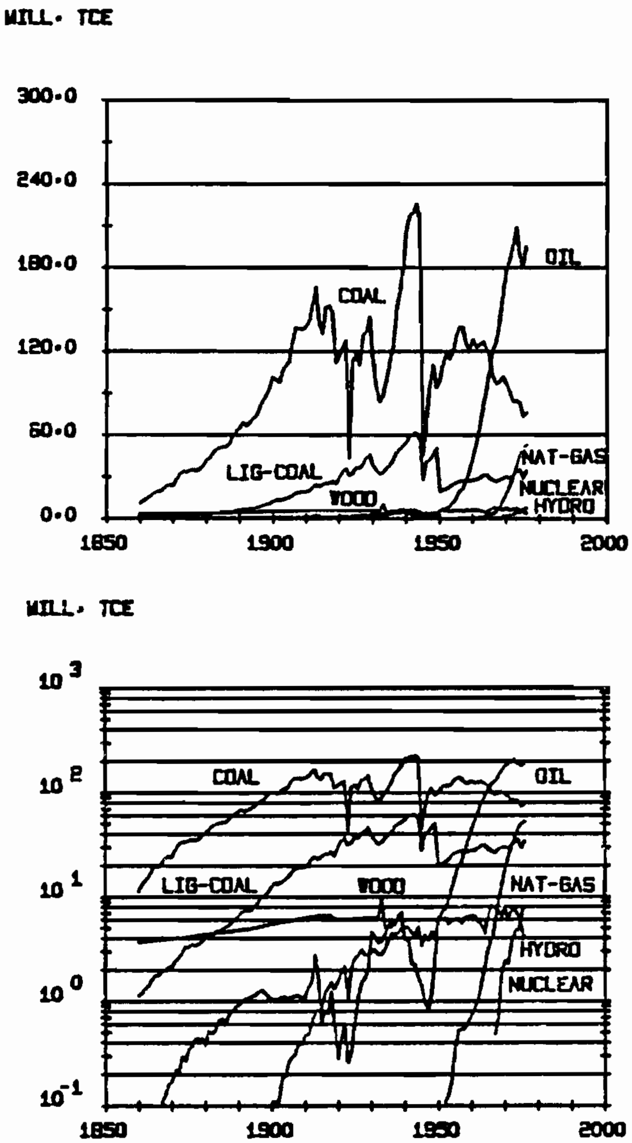


This figure shows the total energy consumption for Germany from 1870 until 1949 and for the FRG from 1950 until 1970. The fluctuations between the two world wars cover a perfect stagnation. It is interesting, if perhaps accidental, that the curve after 1950 matches exactly that before 1910 with the same values and the same growth rate of 4.3 percent. The data after 1950, however, refer to the FRG only.

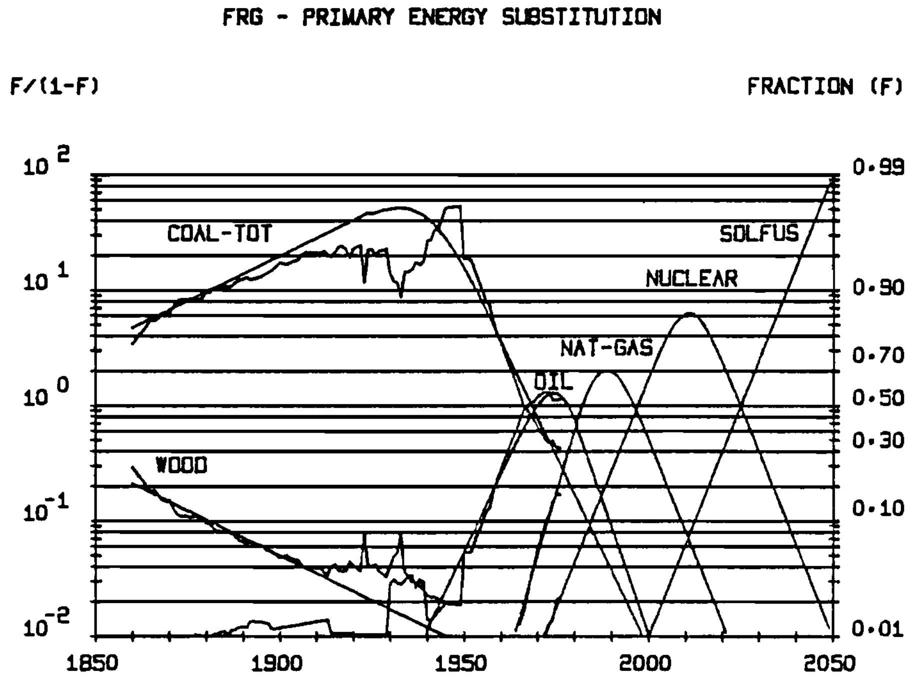
The original data for the period 1870–1974 are taken from Schilling and Hildebrandt (1977), and the data for 1975 and 1976 were calculated on the basis of energy flow diagrams for the FRG given in Kernforschungsanlage Jülich (1977) for 1975 and by Rheinisch-Westfälisches Elektrizitätswerke (1978).

Data on fuel wood consumption from 1870 to 1950 were taken from Putnam (1953) and were converted from British thermal units (Btu) to tons of coal equivalent (tce). No data on wood were available for the last three decades, but during this time wood has had only a marginal share of the market. Nuclear energy inputs, given in gigawatts of electricity (GW(e)) in IAEA (1977), were converted into tce, with a thermal-to-electric conversion efficiency of 33 percent and a utilization factor of 75 percent.

FRG - PRIMARY ENERGY CONSUMPTION



The evolution of energy consumption for Germany and the FRG is shown here for the various primary energy sources, in linear form (top) and in semilogarithmic form (bottom), to emphasize the startup periods. Although a war, a depression, another war, and a partition have had major impacts on total energy consumption, they have had relatively little effect on market shares of the various energy sources, as shown in the following figures.

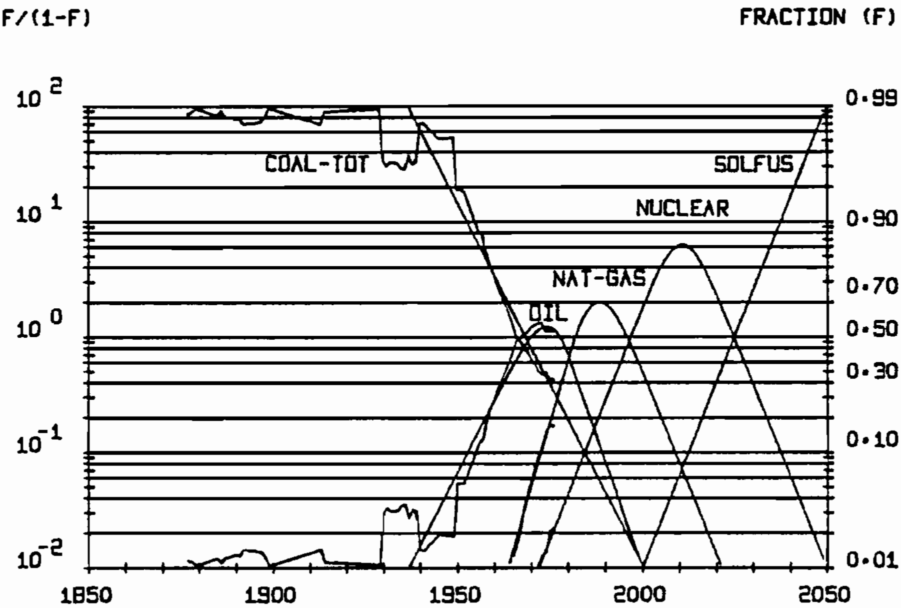

FRG - PRIMARY ENERGY SUBSTITUTION
F/(1-F)
FRACTION (F)
COAL-TOT
SOLFUS
NUCLEAR
NAT-GAS
OIL
WOOD
10 2
10 1
10 0
10-1
10-2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
1850
1900
1950
2000
2050

The logistic analysis is reported here first with wood and then without wood. Since wood statistics tend to be unreliable, they are eliminated to avoid a possible source of perturbation. In both cases, the scene appears fully dominated by coal before World War II. The sudden jump of oil to 3 percent in the thirties from a stationary 1 percent is unexplained and could merit further analysis. It may have something to do with preparation for the war. Between 1945 and 1972, substitution proceeded very smoothly and logistically, with oil becoming dominant with a fairly short time constant of about 25 years, and gas promising the same performance in a suspiciously short period of 15 years. The peaking of oil consumption around 1973 in relative and absolute terms could have been precisely predicted with data up to 1965. Thus, it cannot be attributed to the oil crisis but must result from forces internal to the economy of the FRG. There are, however, two uncertainties hidden in this straightforward projection. First, by analogy with the UK, Belgium, and, up to a point, France, natural gas can continue the fast initial trend beyond the usual 2 or 3 percent before it slows down to its steady penetration rate. No such kink for gas appears in the curve for the FRG. It is possible that the kink may appear later, in which case we will have overestimated its long-term penetration rate.

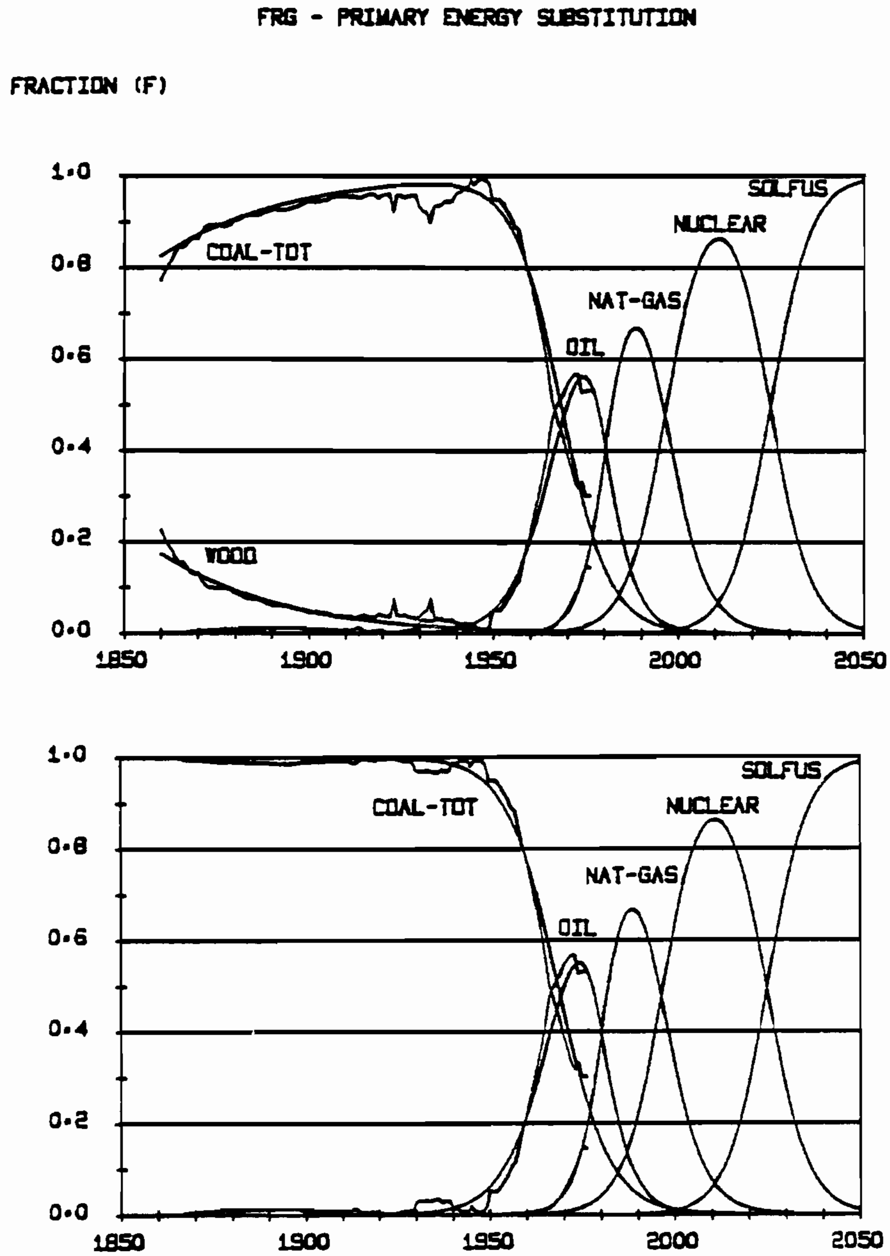
Second, the nuclear penetration rate was estimated on the basis of historical data. However, due to its relatively low share of primary energy (2.2 percent in 1976) we have checked this penetration rate to see that it corresponds to the number of power plants currently under construction and those planned for the future. The IAEA (1977) gives a total installed capacity of 21 GW(th) in 1977 for the FRG; an additional 34.3 GW(th) are now under construction and will be in commercial operation by 1982; and another 65.9 GW(th) are planned by 1985. Taking a rough utilization factor of 75 percent over this period, these plans would indicate approximately 40 million tce nuclear primary energy equivalent in 1982 and 90 million tce in 1985. Our nuclear penetration rate with a total primary energy consumption growth rate of 4.3 percent per year gives a nuclear primary share of 30 million tce in 1982 and 50 million tce in 1985. Thus, our nuclear penetration rate can be characterized as being somewhat pessimistic on the basis of current plans, and presumably realistic as a lower limit on the future role of nuclear energy in the FRG. The true fate of nuclear should be revealed in the next 10 years.

A SOLar or FUSion (SOLFUS) scenario has been introduced for the year 2000, with a penetration rate equal to that of nuclear energy. This keeps the system evolutionary and gives an idea about the ultimate effect of the next source on nuclear. Altogether, the FRG appears to behave normally but more dynamically than systems of similar size and structure, such as France or the UK.

FRG - PRIMARY ENERGY SUBSTITUTION

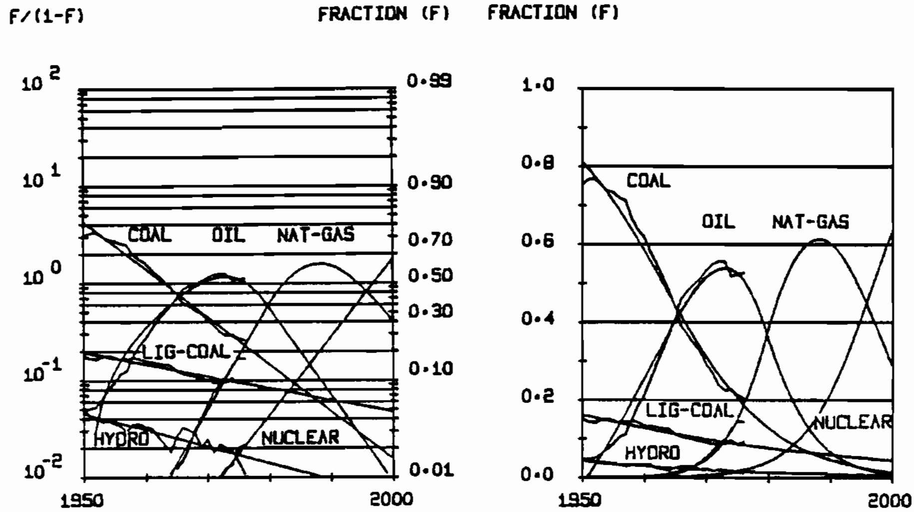


As the statistics on fuel wood are often unreliable, we have eliminated wood and analyzed how the other fuels share the market for commercial energy sources. Oil remains at a level of 1 percent for half a century and shows again that actual logistic market penetration does not start until the market has been penetrated by a few percent. An extraordinary feature of the predictive side of the graph is that oil as a primary source of energy will virtually disappear in the year 2000, a feature common to the UK, the Netherlands, and Belgium. *If this happens to be true, what will automobiles run on?* Perhaps on LNG, H_2, or *methanol*.

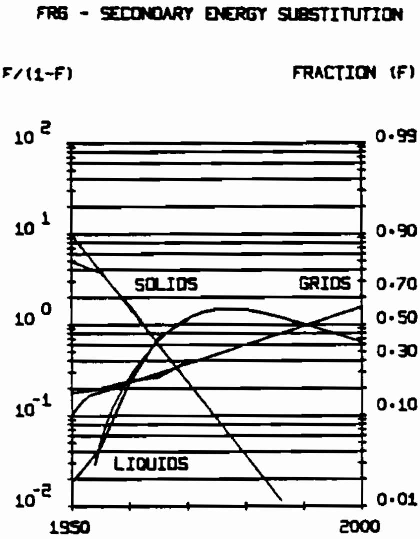


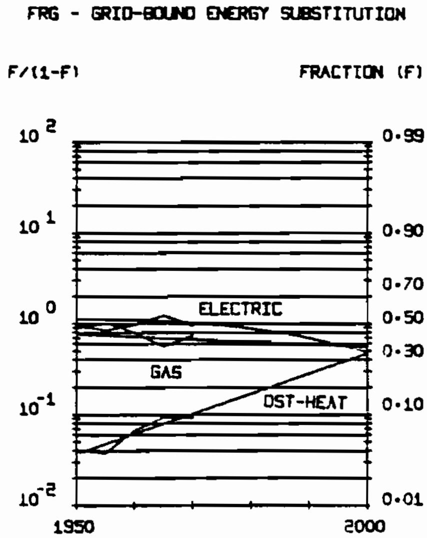
The overwhelming predominance of coal in the German economy prior to 1950 is illustrated again in these linear–logistic plots of the same substitution processes shown in the previous two figures. The upper plot includes wood and the lower plot does not.

FRG - PRIMARY ENERGY SUBSTITUTION



Coal and lignite are usually lumped together in statistics, although, like oil and gas, they are technologically, logistically, and structurally different enough to be considered separately. For the FRG, data are available to treat them independently, which we do in these figures. We also include hydropower, converted to its fuel equivalent by assuming the appropriate thermal power plant efficiency. This separation of the data appears fruitful. Hydropower shrinks in importance, while lignite has its own precise trend and appears to overtake coal in the late eighties. *Can it be a source of fuel for cars, perhaps via methanol?*

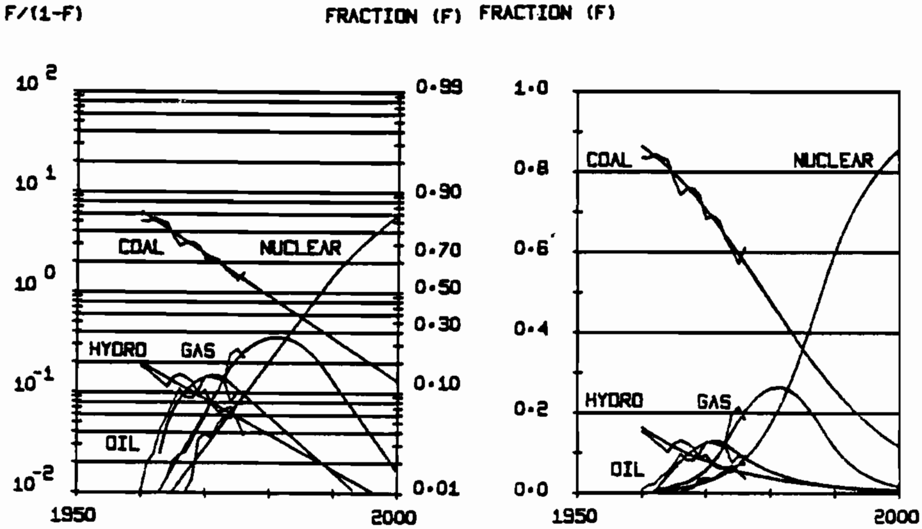




In the same way as we supposed that primary energies are technologies competing for a market, we also assumed that secondary energies behave in the same fashion. The analysis is based on historical data from Sassin (1977).

The left-hand figure shows the market shares of solids (coke, coal, and lignite), liquids (mostly heating oils), and distribution grids (electricity, gas, and hot water) to ultimate consumers in homes, offices, and factories (i.e., excluding the transportation segment of the economy). The right-hand figure shows how the three grid technologies compete among themselves for the overall grid market, revealing a great future for district heating, unless a new system is available in the next 20 years.

FRG - ELECTRICITY GENERATION BY PRIMARY INPUTS

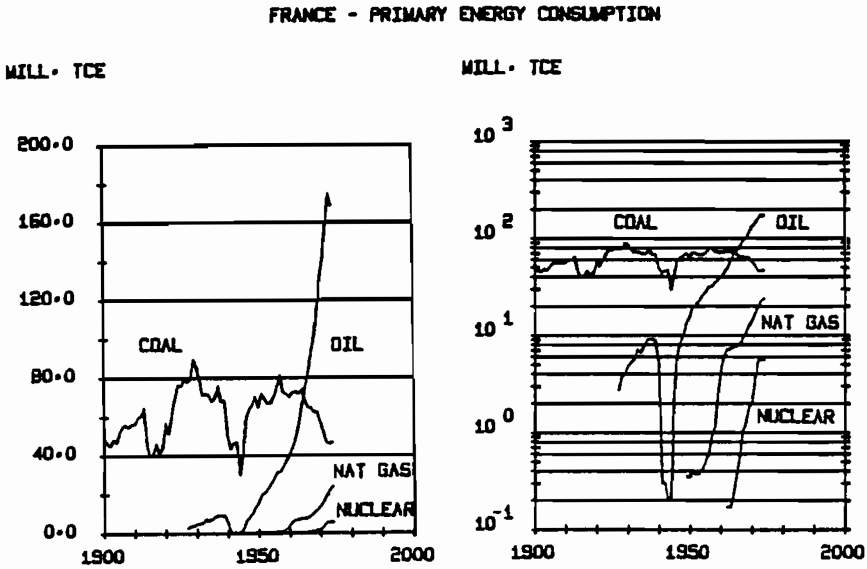


The relatively short data base permits reasonable curves to be fitted. A longer time series would not really help since before 1950 electricity came almost exclusively from coal. The visual impression from the garble of curves is that the FRG electricity industry is undergoing a very fast transformation, with nuclear finally replacing coal in its dominant role with a time constant of about 20 years. If we try to make predictions, *oil* and *gas* appear to fill a transitory gap. Hydropower is phased out of the market simply as a result of market expansion.

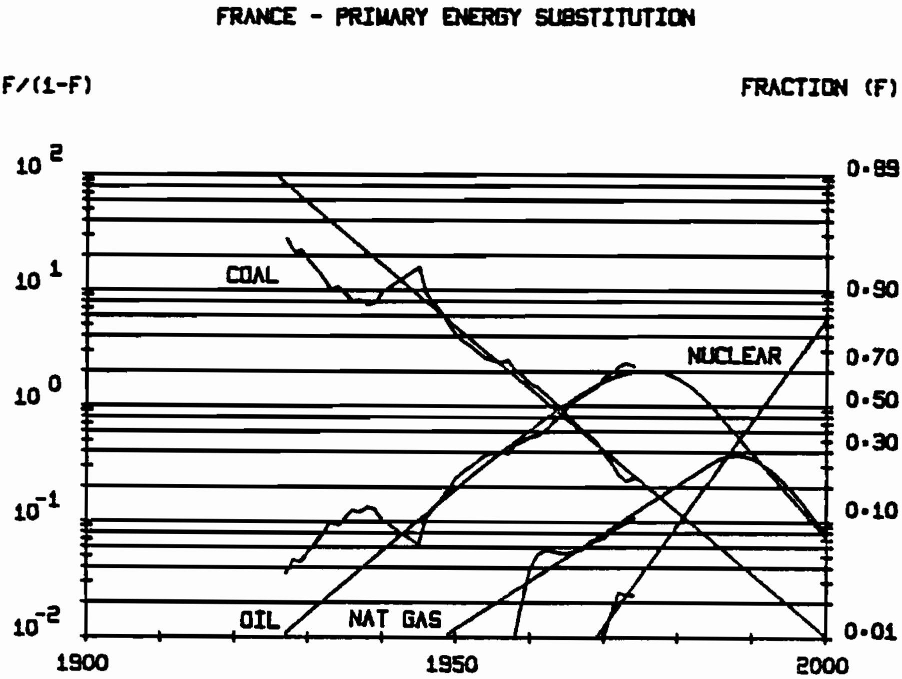
As nuclear is most suited to baseload generation, having very low marginal costs, a question arises about the utilization of part-time capacity available when this baseload is saturated, which seems to occur in the mid-eighties. It is not improbable that this may spur the production of synthetic fuels from nuclear energy, and make the disappearance of oil a little more plausible.

In order to cross-check the consistency of the relatively fast phaseout of coal and lignite in the primary inputs, and the relatively more sluggish disappearance in the electricity industry, we made a check with the assumption that the share of primary energy going into electricity production in the year 2000 will be less than 50 percent. This is not illustrated here, but the projections are consistent.

Data for electricity generation by primary energy source from 1950 to 1974 were taken from Atomwirtschaft-Atomtechnik (1976). Data from 1950 to 1958 were only estimates; thus, we did not use them. The original data are given in gigawatt hours of electricity output. For the purpose of comparison with primary energy consumption, we have converted the data into millions of tons of coal equivalent. However, this conversion is not very exact since we did not account for the different efficiencies of various fuels. Instead, we have taken an overall average efficiency for all inputs. The errors resulting from the approximate conversion to million tce are small. Data for 1975 and 1976 were taken directly from Rheinisch-Westfälisches Elektrizitätswerke (1978) and Kernforschungsanlage Jülich (1977) in millions of tons of coal equivalent.

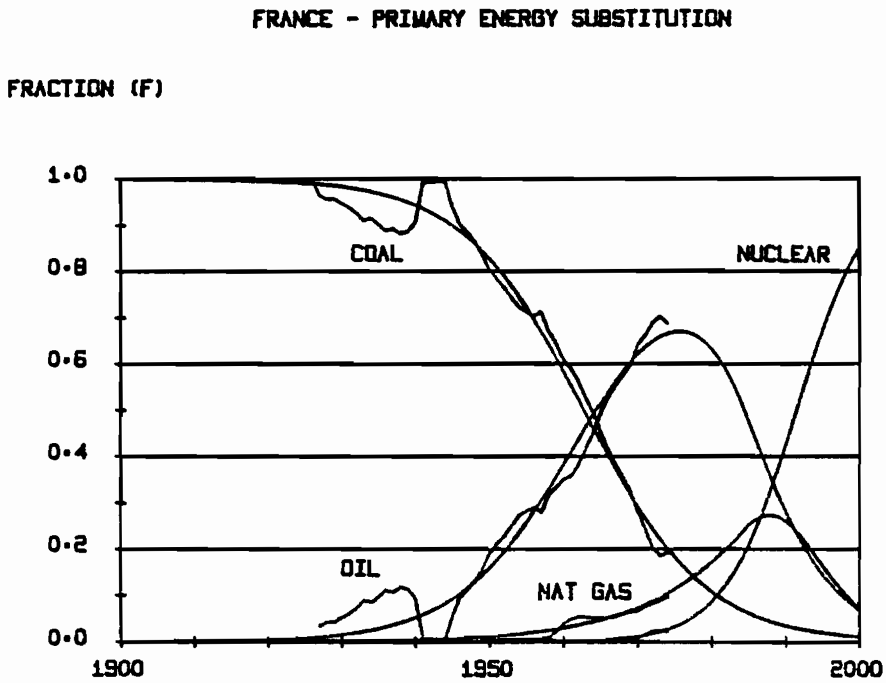


Two sets of data were used for analysis of the substitution dynamics of primary energy for France. The first set is from Weitsch (1976) and was available for the period 1900 to 1974. The second set comes from the OECD (1976). Time series for coal, oil, natural gas, and nuclear are reported in millions of tons of coal equivalent for the period of 1960 to 1974. Oil data contain crude oil and petrochemical products. The agreement of the data sets for the overlapping period of 1960 to 1974 is very good. The first data set is illustrated here in linear and semilog form to amplify the starting period. The second data set is considered later in the report.



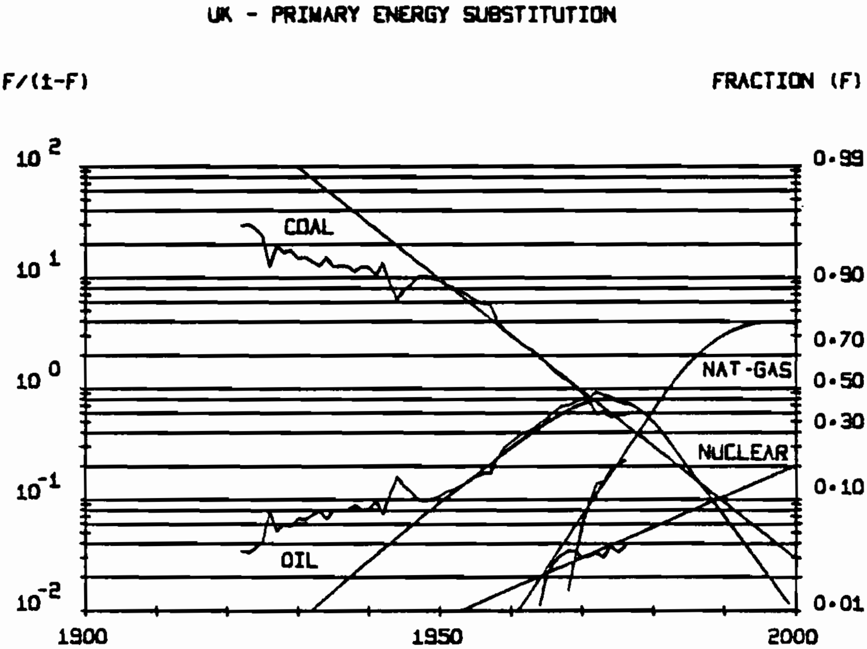
This example of primary energy substitution indicates that France will manage a relatively smooth transition without the very problematic issues seen in the examples for the FRG. Oil was introduced much earlier and will be phased out later, leaving more breathing space for a decision on automobile fuels. The dependence on oil has reached a maximum level of about two-thirds of the total energy consumption. This presumably has greatly stimulated the decisions in favor of the nuclear option; nuclear penetration, however, seems to be slightly slower than in the FRG. Natural gas, which started its career at approximately the same time as in the FRG, may then last a little longer and play the same important role around the year 1990. The very fast growth of natural gas up to about 7 percent of the market might be interpreted as the manifestation of an intensive external support (by the state?), a hypothesis that is yet to be verified.

A peculiarity of the curves is the twist corresponding to World War II. Everything would fit again if we assume that the French system hibernated during the military occupation, and if we "cancel" the 5 years that it lasted. From the linear–logistic plot, France seems to be a much less dynamic system than the FRG. Time constants are in fact about 50 years.


FRANCE - PRIMARY ENERGY SUBSTITUTION
FRACTION (F)
1.0
0.8
0.6
0.4
0.2
0.0
COAL
NUCLEAR
OIL
NAT GAS
1900
1950
2000

As there are so many uncertainties facing the deployment of nuclear energy in the next decade, which is so critical for defining the pace for the rest of its penetration, we made a sensitivity study adopting two other plausible hypotheses. As expected, the penetration of gas is strongly related to that of nuclear, but even oil is strongly influenced. It can be deduced that nuclear is really a hot point in the energy policies of France.

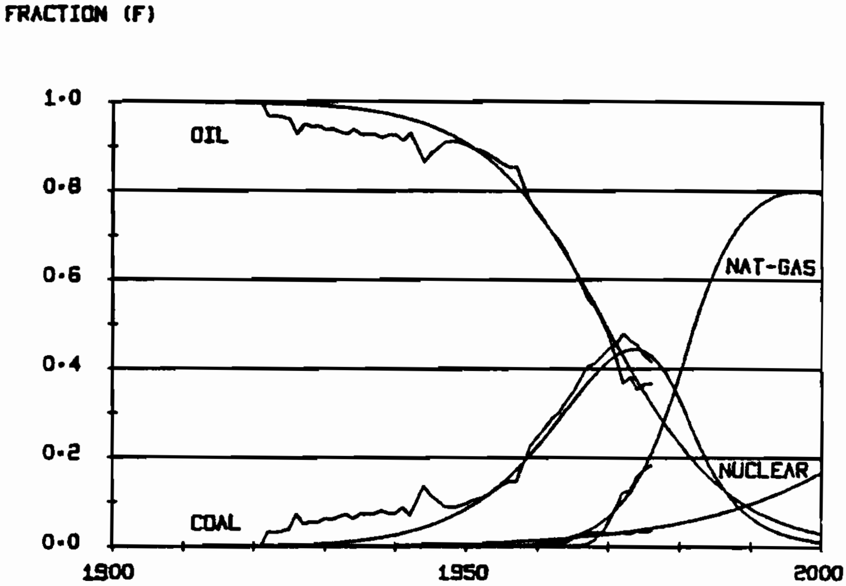
Nuclear energy controlled more than a 2-percent share of primary energy in 1972 after 2 years of very steep growth from a 1-percent share in 1970. This corresponded to 9.7 GW(th) installed capacity reported by the IAEA (1977) for 1972. According to the same source, additional plants with a total of 58.2 GW(th) installed capacity are under construction, with commercial operation expected by 1981. Together, this makes a total of 68 GW(th) installed capacity by 1981. Assuming a very high historical growth rate of energy consumption of 5.6 percent per year (1960 to 1974) and a power plant utilization factor of 75 percent, the nuclear share will be about 14 percent of primary energy in 1981. This calculation shows extremely rapid nuclear construction rates, and if we assume a lower energy demand during the next decade, the nuclear share would be even higher. If historical rates for other substitutions also apply for nuclear, its penetration would be much slower: 8 percent in 1980. We used that rate in our scenario, which therefore should be considered a very prudent one.



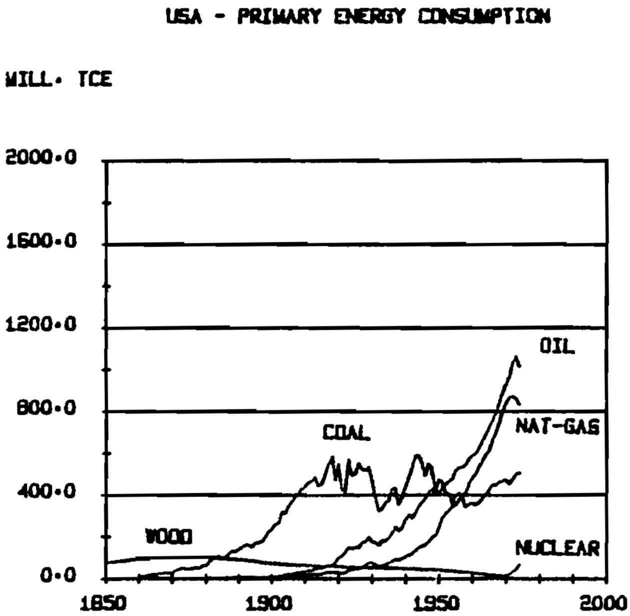
Historical data on consumption levels of coal, oil, natural gas, and nuclear energy for the United Kingdom come from three sources. The period of 1860 to 1950 has been taken from Putnam (1953), from 1950 to 1974 from Ormerod (1976), and 1975 and 1976 from the UK Department of Energy (1976, 1977). Data from Ormerod, however, are reported as fractional shares and therefore absolute levels are not plotted here. According to Putnam, fuel wood has never been an important energy source in the UK except for some use of charcoal. It is not considered in our analysis.

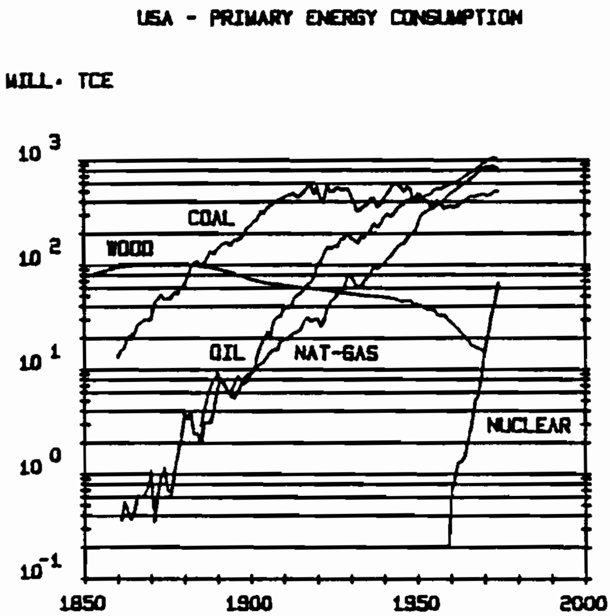
The primary energy substitution is marked by the dominance of coal in the energy market during the last century. Even in 1950, it still contributed 90 percent of primary energy consumption. From 1950 on, the substitution proceeded at high rates. By 1970, oil already controlled a 50-percent share, and natural gas had 10 percent, starting at 1 percent in 1968. However, the natural gas penetration curve has a kink in 1970, which we assume to be indicative of smaller substitution rates to be observed in the future. The very high pre-1970 trend could be explained by the already-existing gas distribution network being fed by city gas, i.e., mainly from coal, which natural gas simply took over and saturated by 1970, so it did not face the usual growth limitations of a new technology. Therefore, we use only points after 1969 to estimate the natural gas penetration trend.

UK - PRIMARY ENERGY SUBSTITUTION



This plot shows that although nuclear energy in the UK had a very fast start in 1964, later it slowed down considerably. Today there are 24 GW(th) of installed nuclear capacity, which at the current utilization rate is about 4 percent of primary energy consumption. Additional plants with a combined capacity of 9 GW(th) are under construction and expected to be in commercial operation by 1979. Another 3.23 GW(th) from nuclear plants are planned by 1986. This makes a total of 36.3 GW(th) installed capacity to be available by 1986. With a utilization factor of 75 percent and the current growth rate in energy consumption of 3 percent per year, this would give a 7-percent market share by 1986; we assumed 6 percent.

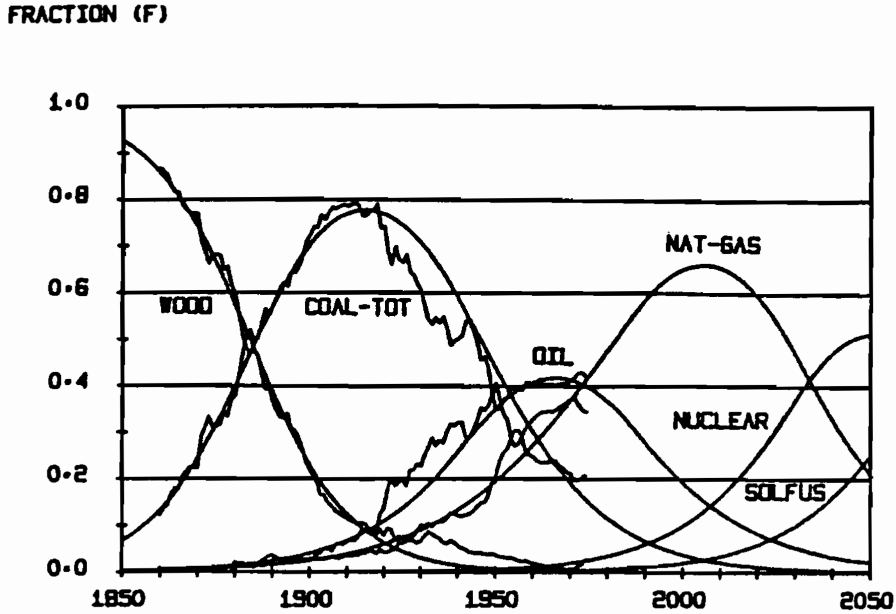

USA - PRIMARY ENERGY CONSUMPTION
MILL. TCE
2000.0
1600.0
1200.0
800.0
400.0
0.0
1850
1900
1950
2000
OIL
NAT-GAS
COAL
WOOD
NUCLEAR


USA - PRIMARY ENERGY CONSUMPTION
MILL. TCE
10 3
10 2
10 1
10 0
10 -1
1850
1900
1950
2000
COAL
WOOD
OIL
NAT-GAS
NUCLEAR

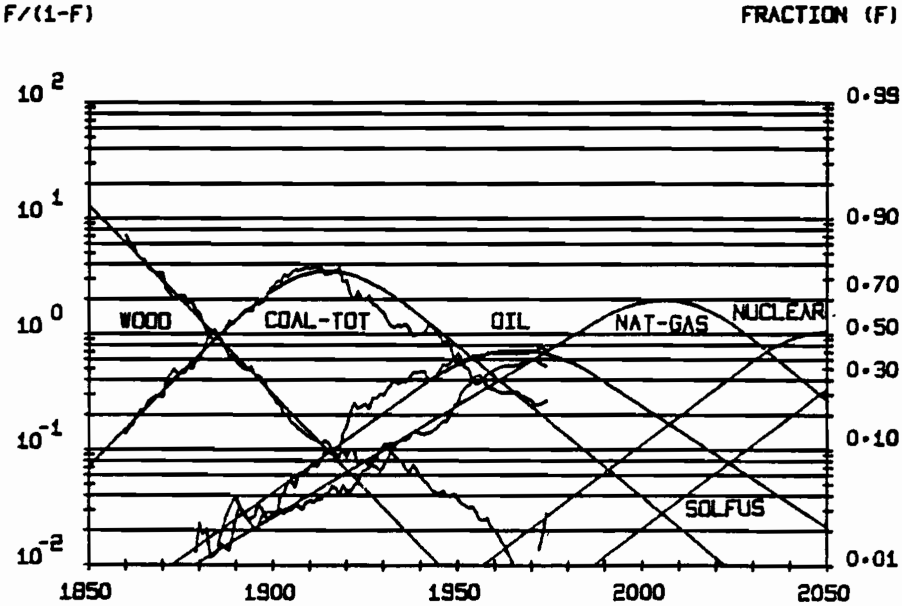
The historical data on primary energy consumption in the United States since 1860 were taken from Schilling and Hildebrandt (1977) for coal, oil, natural gas, and nuclear energy. All data were reported in millions of tons of coal equivalent except nuclear energy. Nuclear consumption rates were reported in millions of kilowatt hours, and we converted them to million tce.

The fuel wood time series come from the U.S. Bureau of the Census (1975a) for the period from 1860 to 1970. The wood consumption after 1970 was neglibible; thus, it was not necessary to add the last few years. The source we used for the data on wood from 1860 to 1945 was Schurr *et al.* (1960), who in turn used two different sources: from 1850 to 1930, Reynolds and Pierson (1942), and from 1935 to 1955, the U.S. Department of Agriculture (1958). Thus, the discontinuity in the penetration rate of fuel wood in the 1930s could be attributed to discrepancies between the two sources.

USA - PRIMARY ENERGY SUBSTITUTION



USA - PRIMARY ENERGY SUBSTITUTION



The logistic analysis again makes order out of the mess of statistical data. Substitution appears to move extremely smoothly until 1920 (facing page, top), in agreement with other economic indicators. Coal peaks around that date and oil at the beginning of the 1960s, 40 years later. As early as 1900, both peaks could have been predicted with good precision; consequently, they are not linked to forthcoming events like wars or embargos. Here, as in all the other cases examined, embargos and large price increases actually produced disproportionately small dents in the curves. The deviation in the lowest part of the wood curve is connected to a change in the statistical source, and most probably due to a change in the accounting and estimating method.

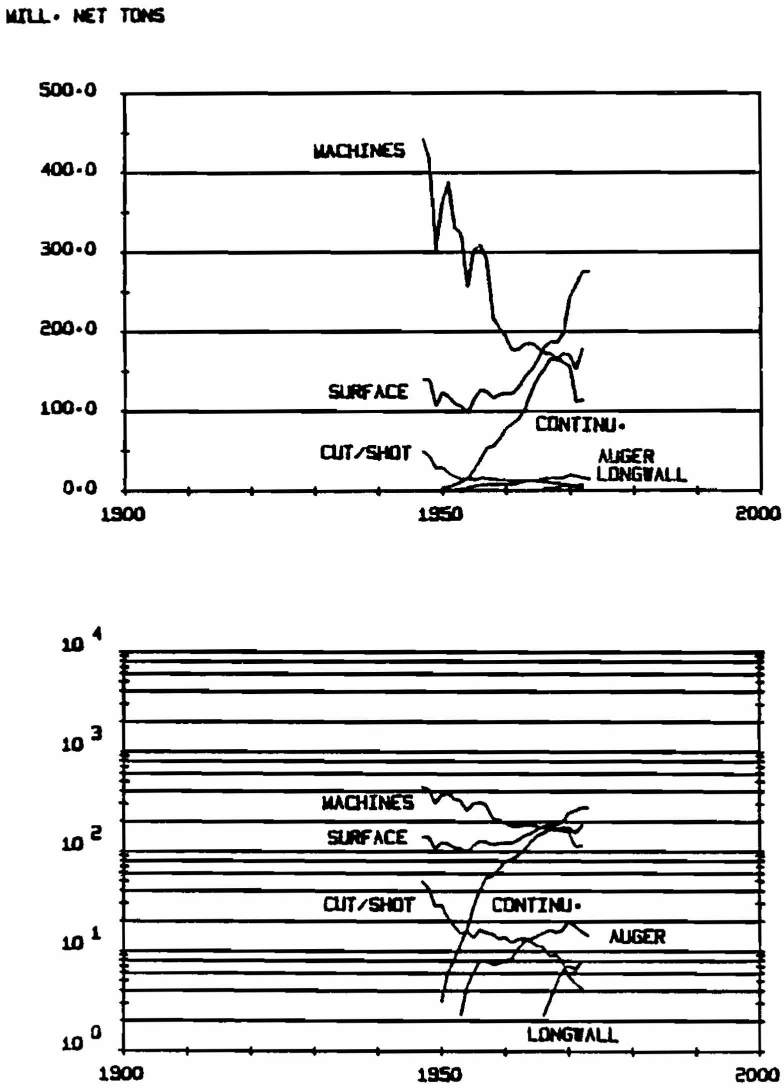
At the bottom of the facing page is a log–logistic plot of primary energy substitution in the United States. One thing left to be explained is the sudden rise in oil production, much above the trend line, essentially during the depression years. This rise induced a corresponding low share of coal, but it did not affect gas. The analysis should perhaps look deeper into the possibility that rapid introduction of automobiles may have caused the perturbation. The striking fact in the process, however, is that after a while, the perturbation was reabsorbed and the secular trend resumed in 1940, 20 years later! This again points to a system memory and clocks!

Contrary to all other predictions, natural gas appears to be the dominating energy source for the next 50 years, which leads to the question whether the United States will import more natural gas in the form of LNG, increase imports from Canada and Mexico, or whether the numerous less accessible sources, like geopressurized zones, will be exploited.

The nuclear market share in the United States was about 3 percent of the primary energy in 1974 and about 5 percent in 1977. This, however, may still not be enough to determine the long-term trend of nuclear penetration rates. By 1990, there should be about 610 GW(th) installed capacity. This estimate is based on the power plants currently under construction and those planned to be in service by 1990 (IAEA 1977). With the long-term energy consumption growth of 3 percent per year, this would imply a 15-percent share in 1990, assuming an overall utilization factor of 75 percent. To account for all possible delays, we assumed a 10-percent share by the year 2000 in our nuclear scenario.

We have also included an alternative future energy source (SOLar-FUSion) that enters the market in 1990 with the same penetration rate as nuclear. There is no basis whatsoever for this assumption, except that a new source could not reach a 1-percent market share before then. As in the world case, a change in the rate of penetration of nuclear will not change the situation of oil, and only after the year 2000 will it change that of natural gas.

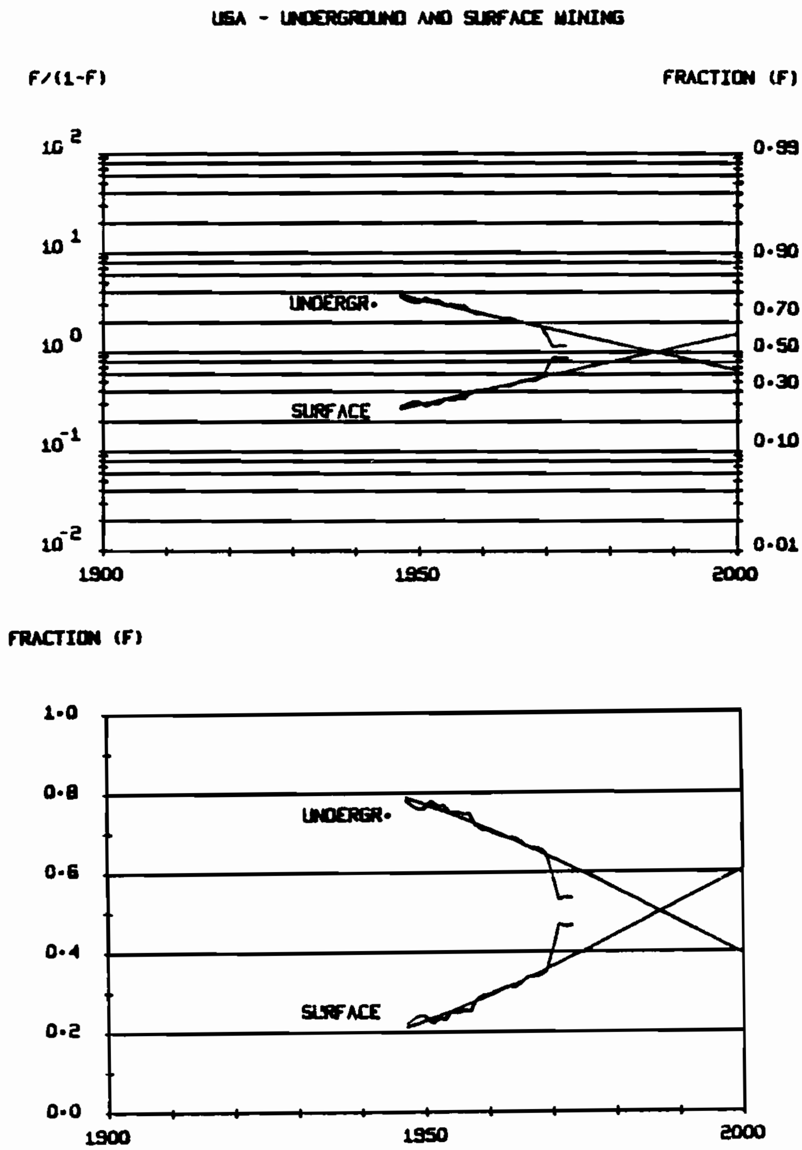
USA - COAL PRODUCTION BY MINING METHOD



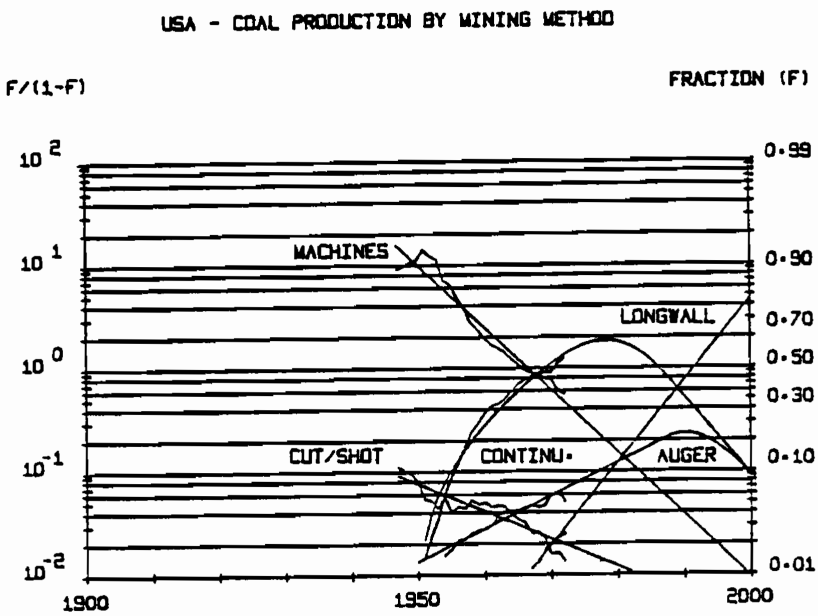
Key:

CUT/SHOT	– cut by hand and shot from solid
CONTINU.	– mined by continuous mining machines
LONGWALL	– mined by longwall machines
MACHINES	– cut by machines
AUGER	– mined at Auger mines
SURFACE	– from surface mines

The evolution of mining techniques in the United States is examined here. It is a very appropriate field for logistic substitution analysis. In these two figures, the amount of coal extracted according to the various techniques is reported on linear and semilog coordinates. As usual, no simple patterns appear.



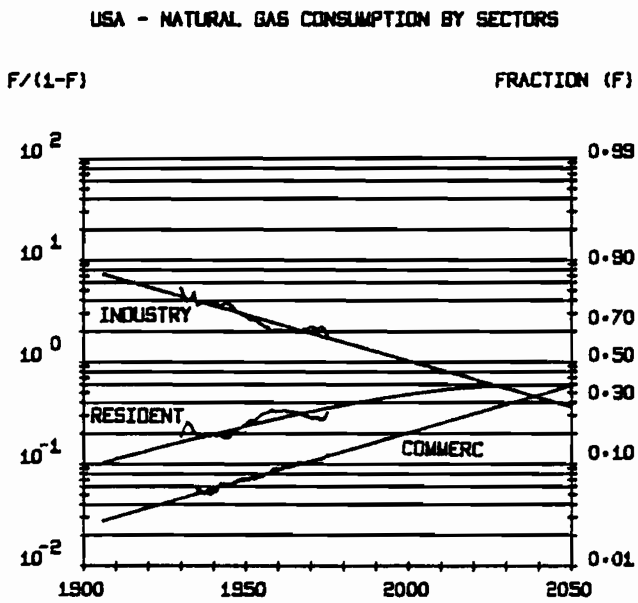
USA - UNDERGROUND AND SURFACE MINING
F/(1-F)
FRACTION (F)
10 2
10 1
10 0
10-1
10-2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
UNDERGR.
SURFACE
1900
1950
2000
FRACTION (F)
1.0
0.8
0.6
0.4
0.2
0.0
UNDERGR.
SURFACE
1900
1950
2000



Due to the increasing dominance of strip mining, the competition between strip mining and underground mining is dealt with explicitly (see facing page). A check of the total amount extracted shows that the sharp kink in the logistic plot is due to a sudden drop in deep mining production. These sudden drops are not new in a socially turbulent structure like the U.S. mining industry, but this time it may be due to the introduction of stringent safety rules in the mines. Most probably, the perturbation will be reabsorbed in a few years. If not, deep mining would disappear in the United States in 1980, a very unlikely if not impossible occurrence. Strip mining legislation seems to bring in the corrective reaction.

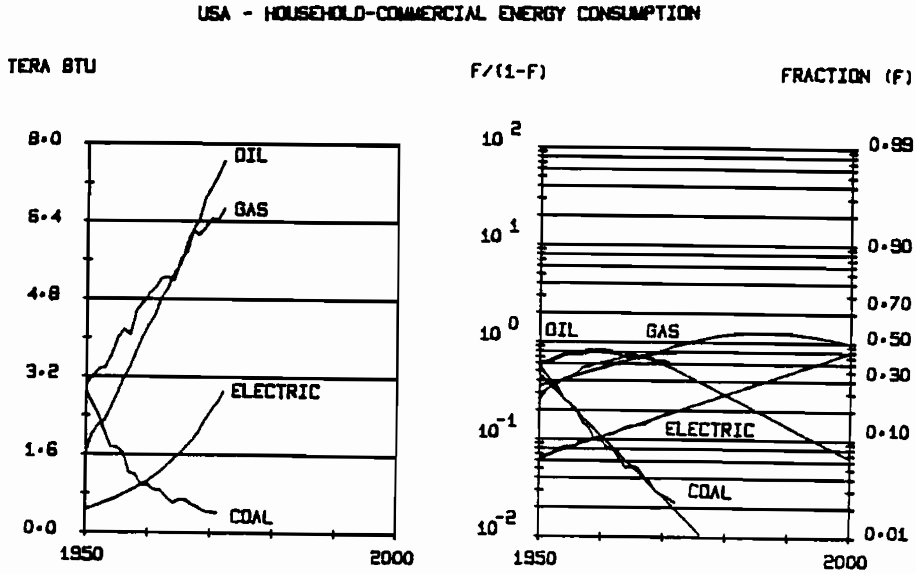
As deep mining presents such an array of competing technologies, it is interesting to analyze their struggle, leaving out all surface mining techniques except Auger, which could be considered as both underground and surface technology. The longwall technology becomes dominant in the next 20 years, winning the last battle of a lost war, as underground mining seems bound to disappear in about 50 years.

With ups and downs, coal production in the United States stayed constant over the last 50 years at a level of about $0.5 \cdot 10^9$ tons/year. Since the phaseout of coal in the United States is a slow process, during the next 20 years, the U.S. mining industry should equip longwall mines for production that is slightly larger than the total production of FRG coal mines now. The abbreviations are defined on page 42.

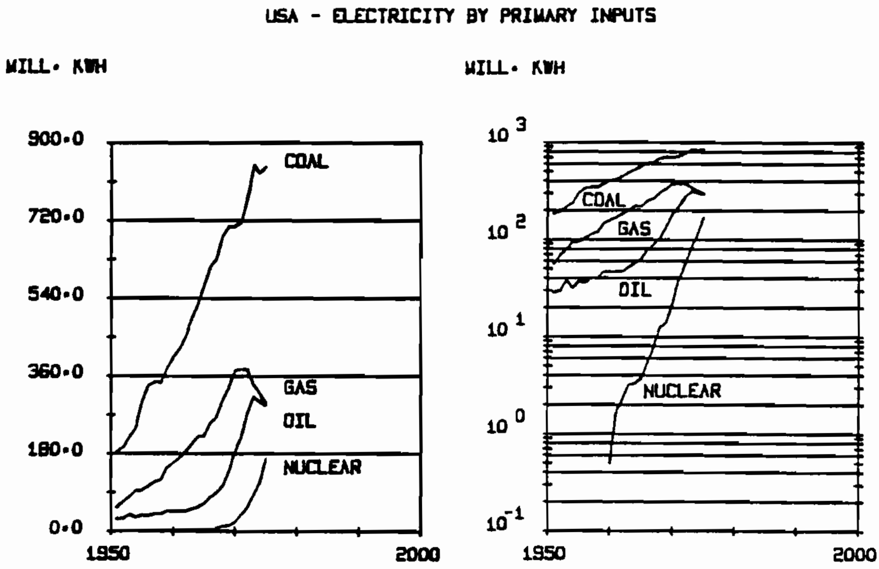


When we view the system through dynamically competing subsystems, we may think that *different branches of the economy compete for the same resource*, a statement much in line with the *Weltanschauung* of economists and laymen. In this spirit, we made a logistic analysis of the shares of natural gas consumption of three large parts of the U.S. economy: the industrial, the residential, and the commercial.

It appears that the small consumers are gradually winning a larger share of natural gas, which is quite reasonable in view of how simple it is to use and how little it pollutes. The process of competition, however, appears to have long time constants, and only in the year 2050 will the natural gas input be equally distributed among the three competitors.

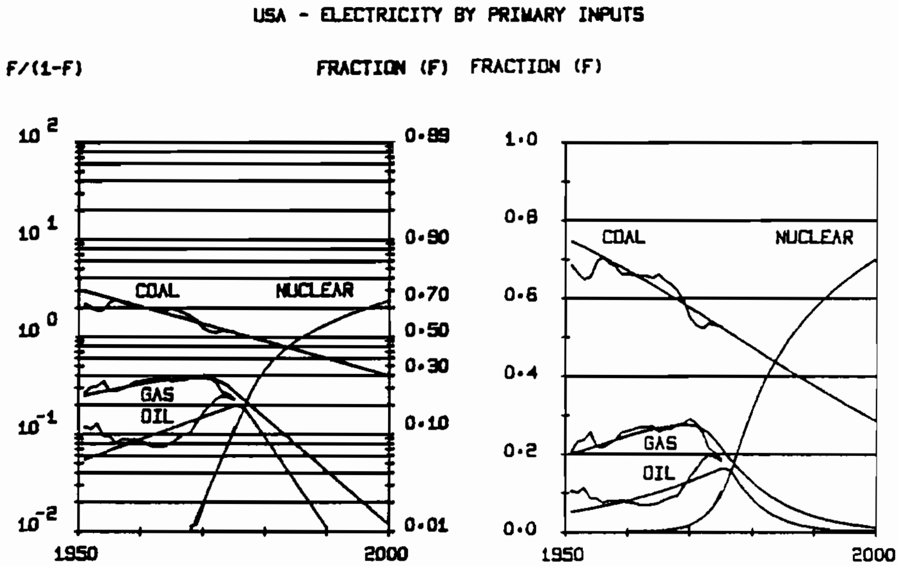


Reversing the previous reasoning, one can think that the various forms of energy compete for a certain sector. In this case, it is the household–commercial sector.



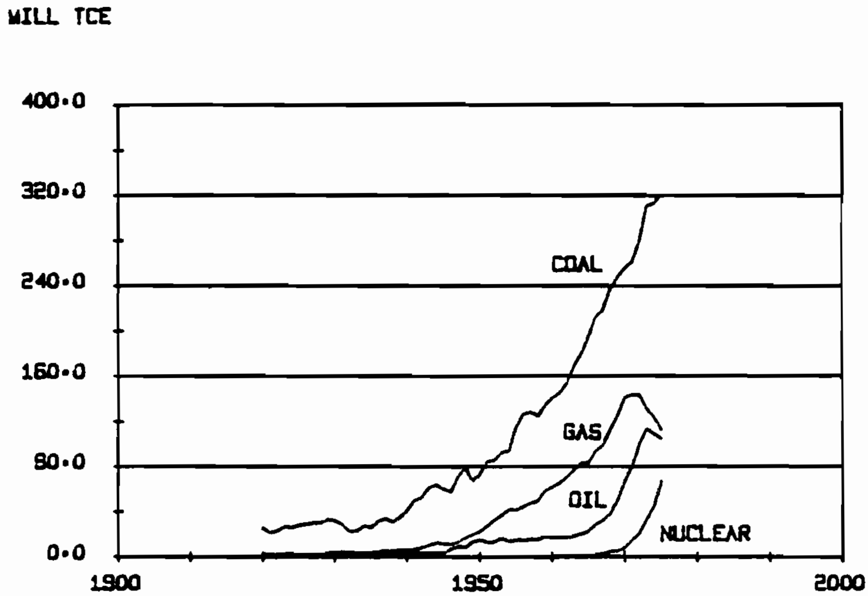
The electrical utility market is very important for primary energy producers. It is large, fairly homogeneous, highly technological, and rather profitable. Therefore, it is a good test-bed for observing the progress of new technologies. In these two figures, we plotted the evolution during the last 25 years of the production of electricity according to the various primary fuels, both in linear and semilog form.

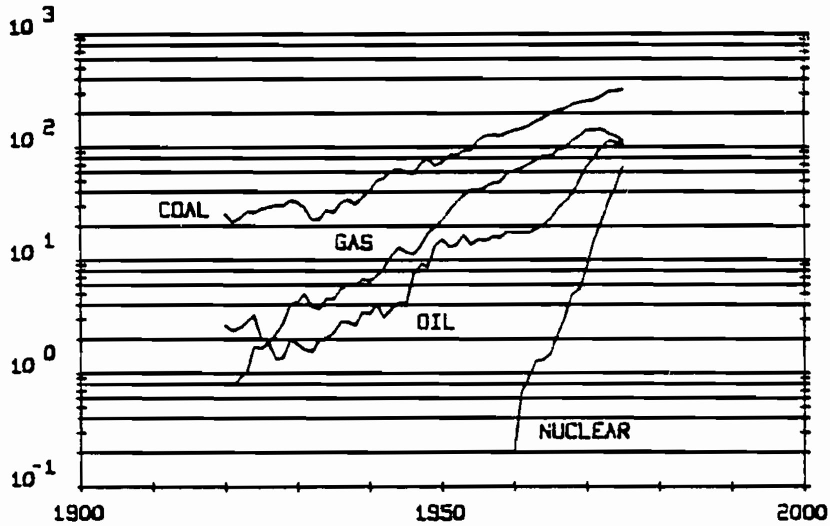
The historical data on electricity generation according to primary energy fuels in millions of kilowatt hours (kWh), as well as the data on primary energy consumption for electricity production in billions of British thermal units used later in this report, have been taken from the U.S. Bureau of the Census (1975, 1976, 1977). The two data sets show implicitly the relative conversion efficiencies for electricity generation according to the various energy inputs used.



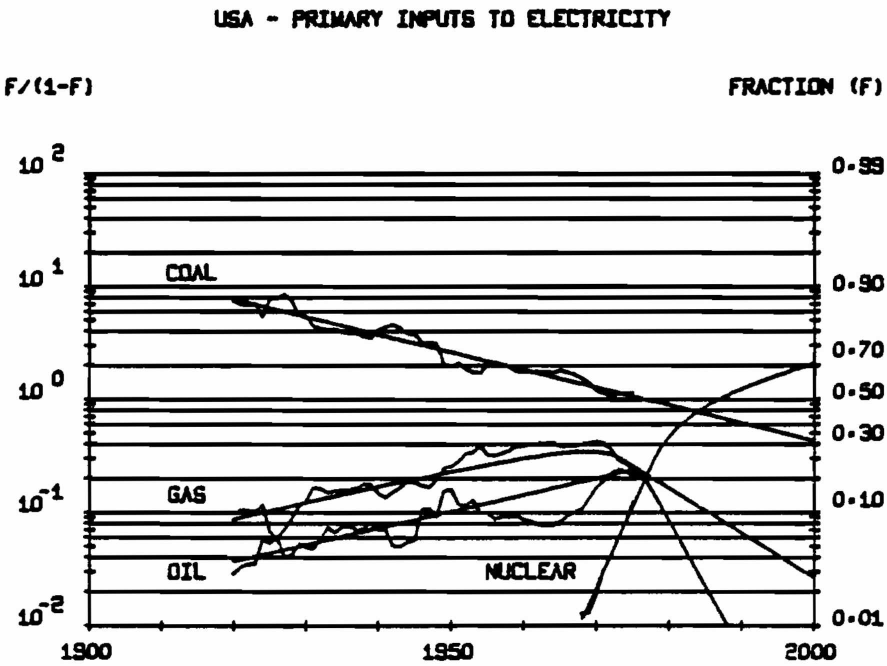
Electricity generated using coal, oil, or gas is shown here in a logistic representation. This is an indirect way of showing the competition of the various primary energies.

USA - PRIMARY INPUTS TO ELECTRICITY

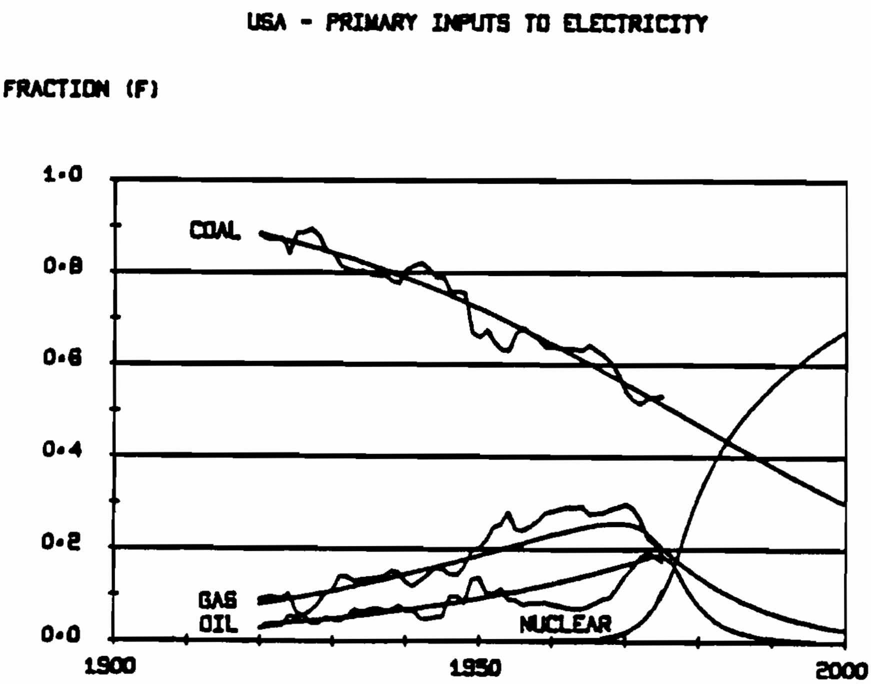




Here the competition is expressed more explicitly in terms of millions of tons of coal equivalent (tce) of different fuels entering the electricity market. It is clear that coal has been under constant attack by oil and gas, which have progressively eroded its position. A perturbation appears in the period from 1955 to 1970, showing an excessive consumption of gas with respect to oil. This may appear strange since during this period oil was "cheap and abundant." But in the United States, gas was still cheaper because of stringent price regulation. Oil recovers, however, and regains its position from 1973 to 1974!



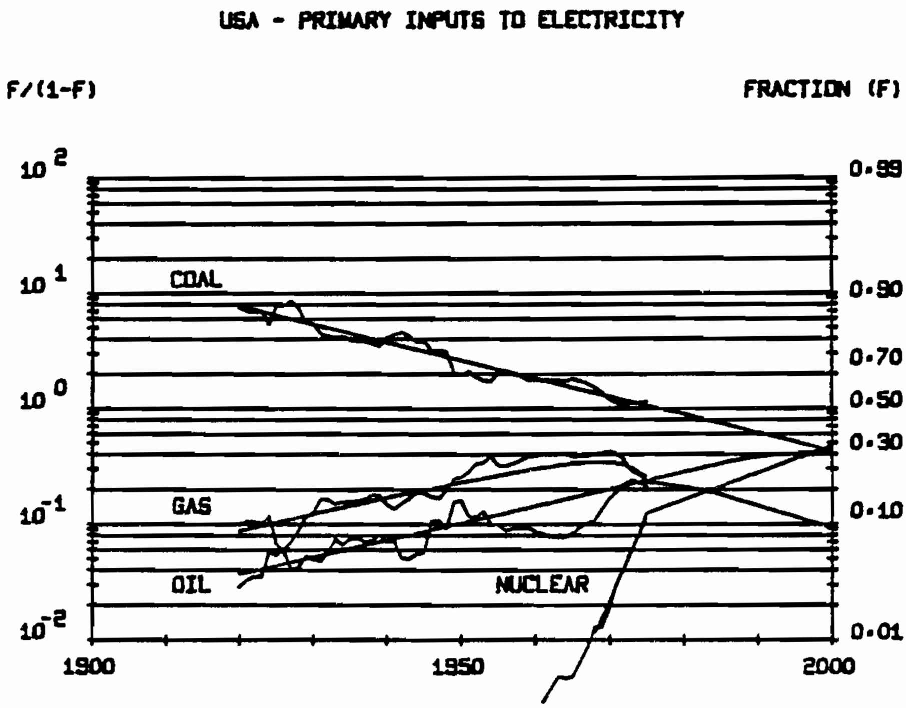
USA - PRIMARY INPUTS TO ELECTRICITY
F/(1-F)
FRACTION (F)
10^2
10^1
10^0
10^{-1}
10^{-2}
0·99
0·90
0·70
0·50
0·30
0·10
0·01
COAL
GAS
OIL
NUCLEAR
1900
1950
2000



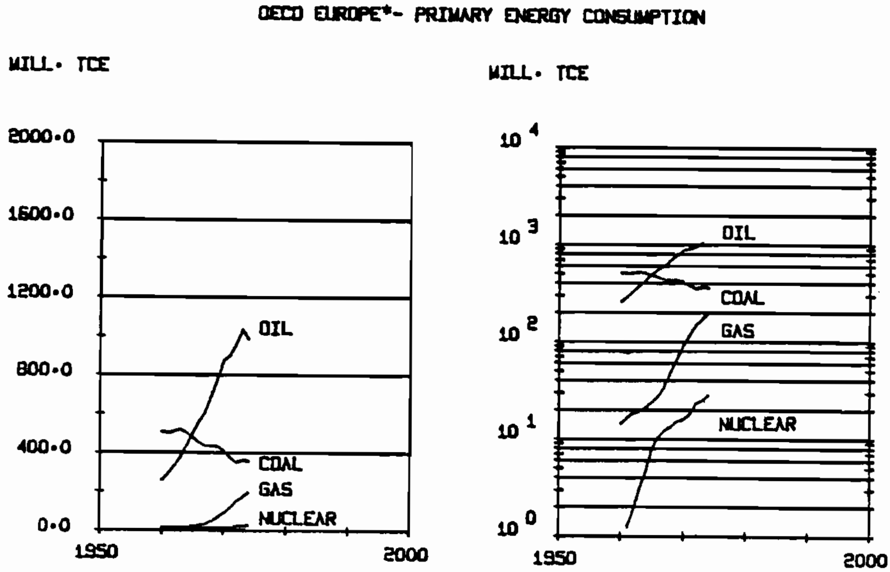
USA - PRIMARY INPUTS TO ELECTRICITY
FRACTION (F)
1·0
0·8
0·6
0·4
0·2
0·0
COAL
GAS
OIL
NUCLEAR
1900
1950
2000

The substitution of different primary inputs in electricity generation is discontinuous when nuclear enters the market with a powerful drive and phases out oil and gas before the end of the century (facing page, top). Coal appears perfectly unperturbed and finally dictates the pace of introduction of nuclear from 1980 on. It is interesting, even if a little shocking, that this pace had been finally determined by the penetration rates of oil and gas *in the twenties*. Many problems surface from the expected structure of the system in the next 20 years. For example: What kind of peaking system will be provided? Will it be through medium-Btu gas from coal and gas turbines or through storage?

The lower figure on the facing page reports the same results but in linear terms in order to make it easy to interpret. Connected with the fast substitution of nuclear energy in the electricity market is the possibility of a kink in the nuclear penetration curve during the coming years, leading to lower market substitution and a smooth transition.

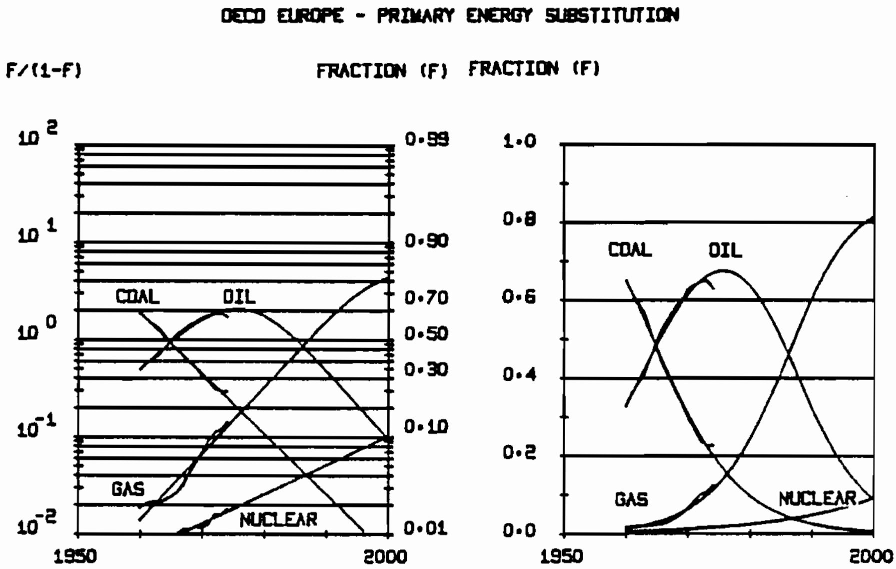

USA - PRIMARY INPUTS TO ELECTRICITY
F/(1-F)
FRACTION (F)
10 2
10 1
10 0
10-1
10-2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
COAL
GAS
OIL
NUCLEAR
1900
1950
2000

When the nuclear energy penetration of the market is plotted starting with a market share lower than the 1-percent share reached in 1967, no change of the substitution rates can be observed; in most other examples, nuclear energy and natural gas stabilize to a slower penetration rate once they take a few percent of the market (e.g., for nuclear energy see pages 31, 33, and 36, and for natural gas see pages 33, 36, 63, and 66). Assuming that this kink will occur before the end of this decade, we observe higher natural gas and oil shares, and coal remains unaffected. The nuclear share in the year 2000 is more than halved to about 30 percent. This slower penetration of nuclear energy has been determined by a scenario based on the nuclear share in 1976 and the expected share in 1990 calculated from the nuclear installed capacity under construction and the planned power plants (610 GW(th); see page 41), and the historical growth of the electricity market at 6.2 percent per year. The result is sensitive to the value for that historical growth.



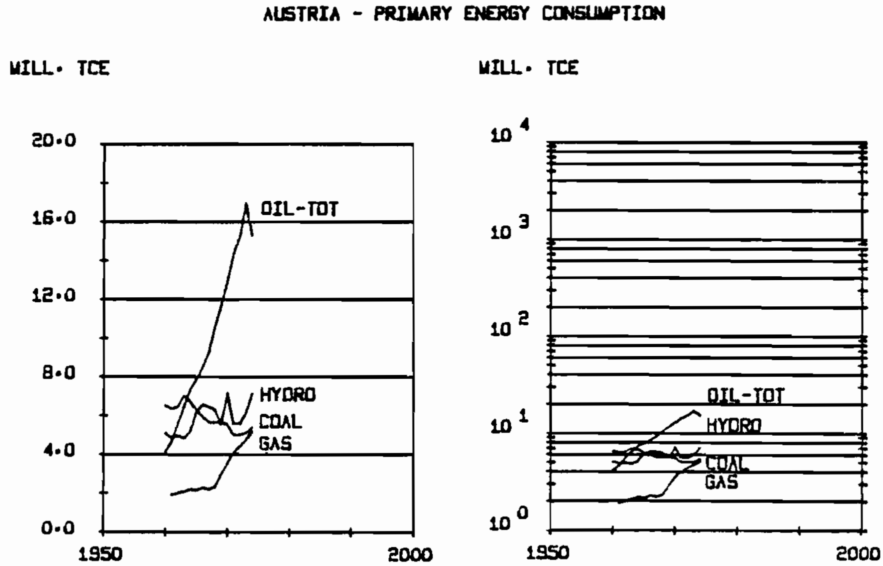
The data come from the OECD (1976). We made a logistic analysis for the European OECD states lumped together and for some of the states separately. The data base is relatively short, 15 years, but the curves appear very stable. The overall OECD case is presented here.

*Austria, Belgium, Luxemburg, Denmark, Finland, France, FRG, Greece, Iceland, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland.



The logistic analysis for OECD is presented here in the log and linear form. Coal and oil behave very regularly. Natural gas has prolonged the start-up vagaries up to 10 percent of the market. The fact that it shows a penetration rate virtually identical to that of oil is a sign that tends to confirm the good quality of the projections. Nuclear has penetrated only to 2 percent; consequently, the projection is still somewhat uncertain. Any change in rate, however, would not change the projection that gas will become the next dominant primary energy source.

Two facts emerge; one is that natural gas, with a penetration rate much similar to that of oil, appears to be the primary source in the year 2000. It appears to drive oil to an impressively low level of 10 percent in that year. Second, the curve for nuclear seems quite regular, although the definition of the final substitution rate is still open owing to the current low level of penetration. With the present rate, nuclear would reach a somewhat unimpressive share of 10 percent of the market in the year 2000, leaving Europe completely dependent on hydrocarbons. SOLFUS has not been included as a scenario. It would possibly make nuclear saturate the market during the first half of the next century.

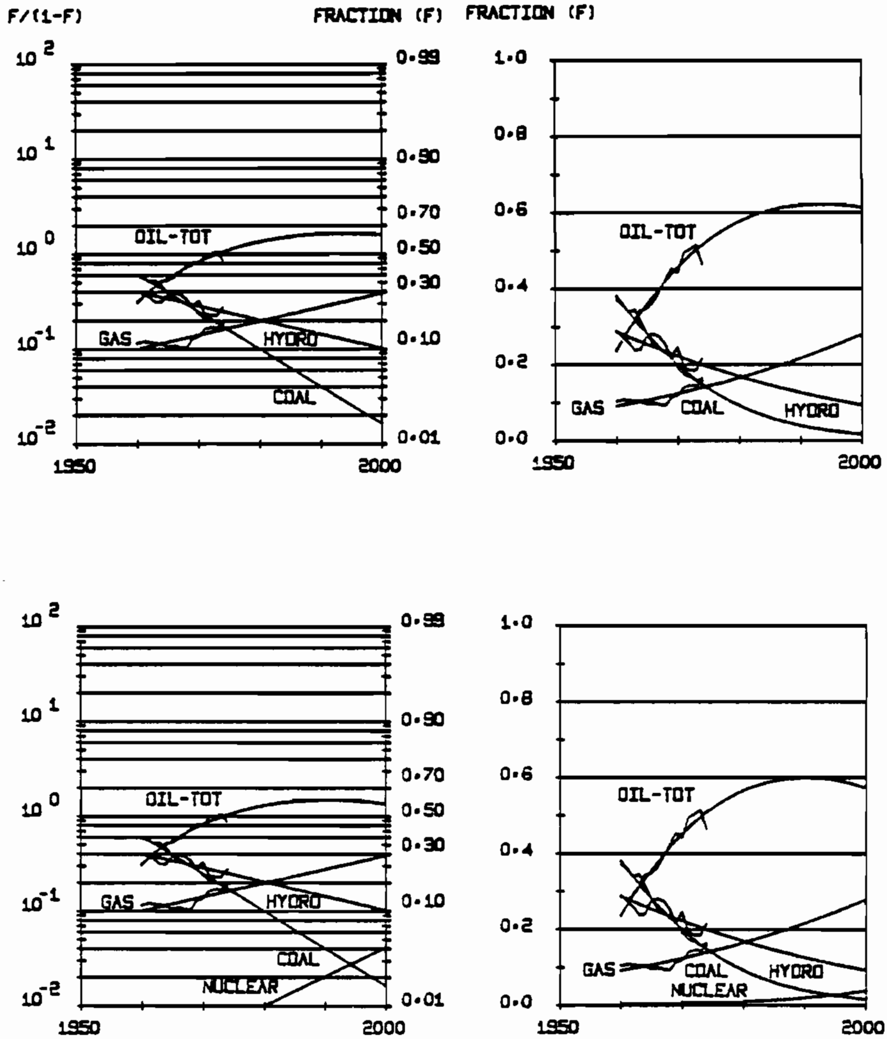


The primary energy consumption for Austria displays minimal dispersion except for rapid growth in oil consumption. Hydropower has been included in the set of primary energies because it is quite an important energy source for Austria. The market appears dominated by oil, with natural gas still low but increasing fast.

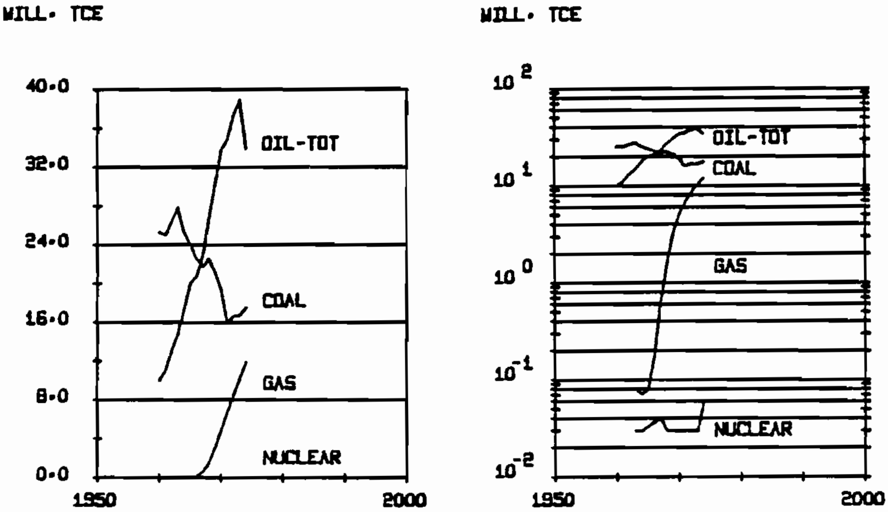
On the facing page, the data are presented in the log and linear logistic format. In the first row, no new sources are introduced. This may not have many consequences before the year 2000 because the time constant of the country appears to be so large (about 100 years). The situation with respect to nuclear is extremely confused. One power station was built but is not in operation owing to a referendum. No second power station is in sight, but nuclear electricity is being imported from neighboring countries.

The figures in the second row should then be considered as a sensitivity analysis indicating the potential influence of nuclear energy on the other primary sources. If we hypothesize a 4-percent penetration in the year 2000, the medium-term effect would be a slight reduction of oil imports. Gas consumption would be affected only after 2020. Only an improbable, very fast nuclear penetration could make Austria reasonably independent of oil in the next 30 years.

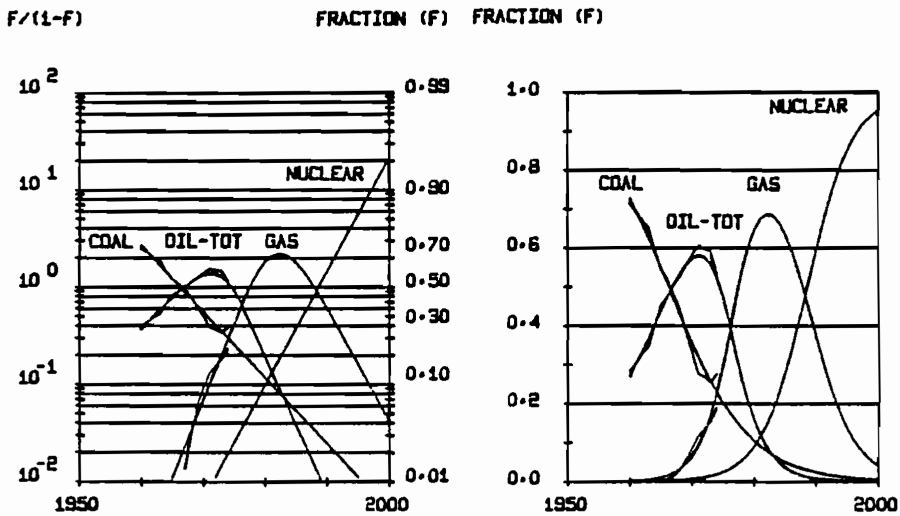
AUSTRIA - PRIMARY ENERGY SUBSTITUTION



BELGIUM - PRIMARY ENERGY CONSUMPTION



BELGIUM - PRIMARY ENERGY SUBSTITUTION

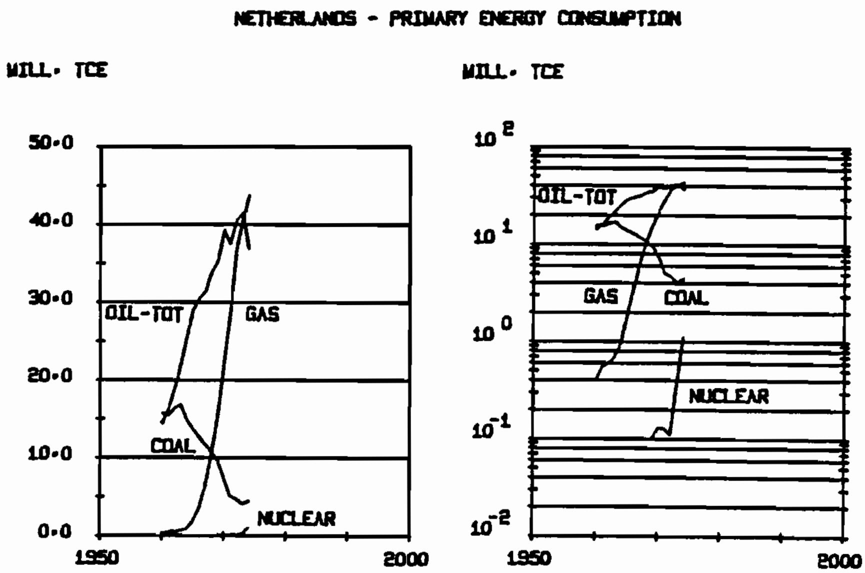


Without logistic analysis, the data on primary energy consumption in Belgium suggest that oil is the dominant primary energy, with no limits to its future (upper figure on the facing page). Coal is rapidly phasing out and gas is phasing in. Nuclear is barely perceptible (in 1974).

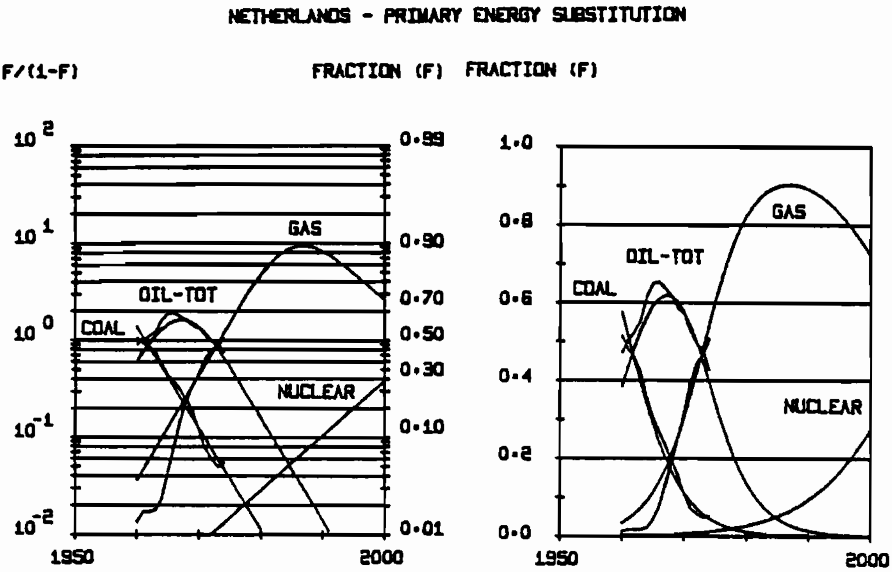
In the lower figure, logistic analysis reveals the hidden order. Although the data cover a short period of time, the good quality of the fit gives weight to the following considerations.

Coal seems to disappear around the year 2000, which is more or less in line with the ideas in the country. Oil, including the trade balance in oil products, peaks around 1973 and seems to phase out in 1990. This prediction, which, by the way, repeats itself in a similar form for the Netherlands, the FRG, and the UK, is a bit hard to swallow on technical grounds. How will cars run in 1995? Will they use increasing amounts of methanol produced from coal and natural gas? This would in fact preserve their compatibility with gasoline, necessary at least for long-distance traveling. If coal is the primary source, a new curve may be required for underground coal gasification, i.e., for new coal. Electric, hydrogen- or methanol-electric, and pure hydrogen cars are in principle possible, but do not seem very probable in this time period.

We could also have overestimated the rate of penetration for gas. External interests prop up the penetration of a new technology at very high rates, usually until it has penetrated a few percent of the market. One could make the hypothesis that a particularly favorable environment, in this case the prior existence of an efficient distribution net for gas, and the spacial concentration of population, has prolonged this initial stage up to 10 percent. Yet, a change in the penetration rate from that point would only delay the disappearance of oil by a few years. A similar tampering with the rate of penetration of nuclear, which is still fairly hypothetical because of many lingering doubts, shows other possible small gains, but is not really decisive. So the problem is substantially left open. If we believe in the predictive capacity of our methodology, something fairly drastic will occur in the automotive field during the next 20 years, and the focal area will be in Belgium, the Netherlands, or the FRG.

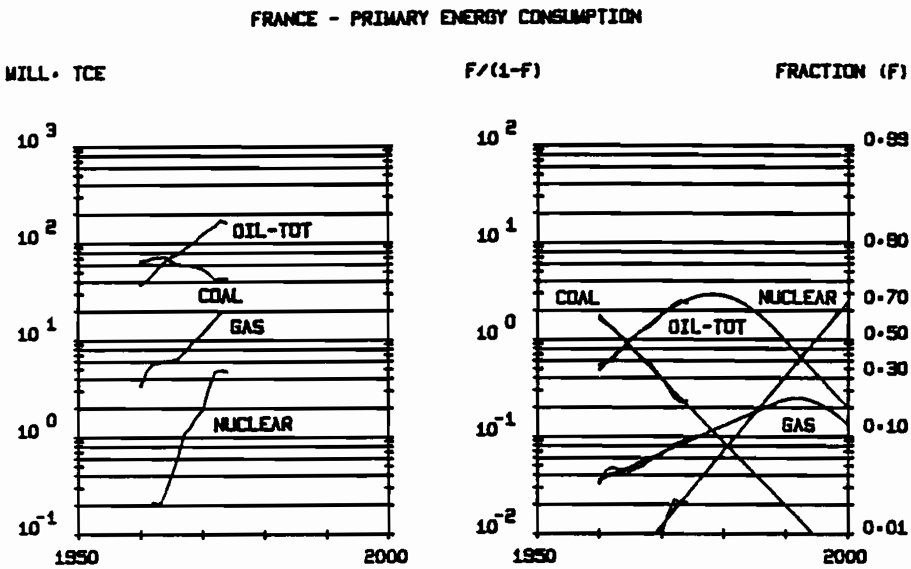


Primary energy consumption in the Netherlands is here reported by primary source, in linear and semilog form to stress the starting period. No particular tendency emerges; coal is phasing out and oil is phasing in. Gas made a very fast inroad after the discovery of the Gröningen field. Nuclear is just emerging.

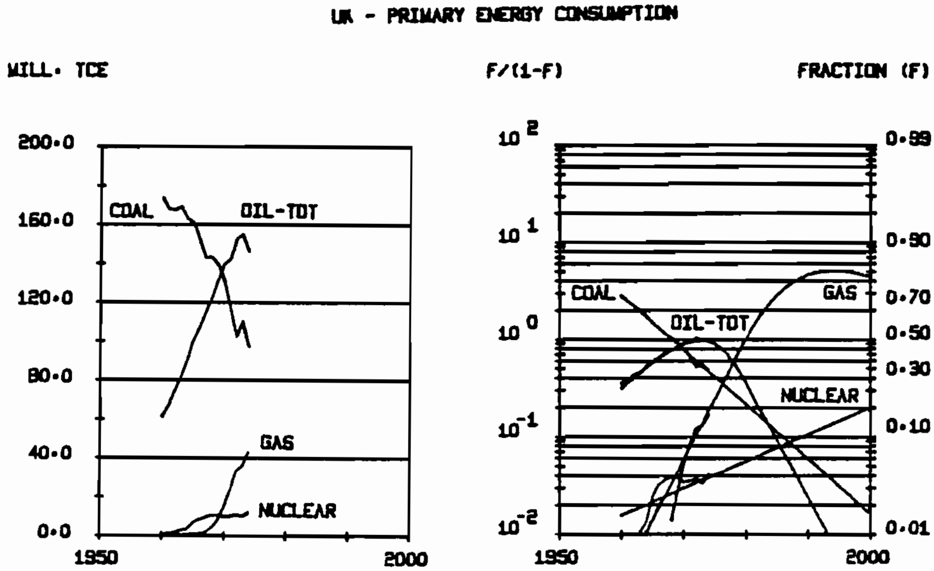


The logistic analysis shows here a quite precise structure. Coal is bound to disappear in 1980 and oil in 1990, opening the question about cars discussed already in the case of Belgium. The problem of nuclear is perfectly open and our scenario is pure guessing. It must be clear that if nuclear electricity is imported in spite of antinuclear opposition, nuclear should still be included in the energy budget. However, since natural gas has such a dominating role, the rate of introduction of nuclear energy will have little influence on the fate of oil. Thus, the car question is left open.

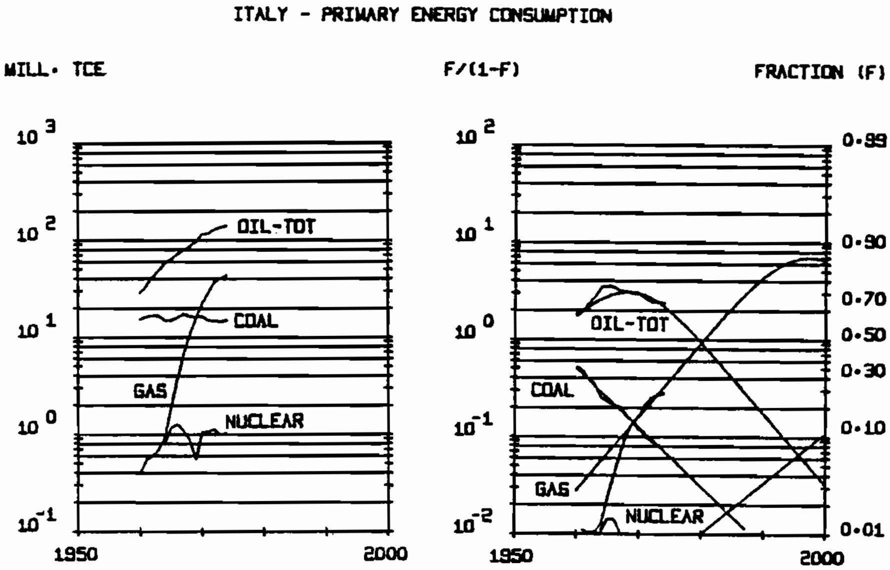
Seen in the light of our analysis, the Netherlands' alternatives appear to be natural gas or nuclear, and, thus, one understands better the importance of the debate about nuclear energy.



The primary energy substitution for France is repeated here using OECD data sources. The result is substantially the same as on page 33, although different data and a shorter data base are used, which leads to minor discrepancies in the long run. For the nuclear scenario we estimated an 8-percent penetration in 1980, which comes from the fitting of the data, although the current market share is still below 2 percent. However, nuclear energy is growing fast in France and the situation should become clear in a few years.

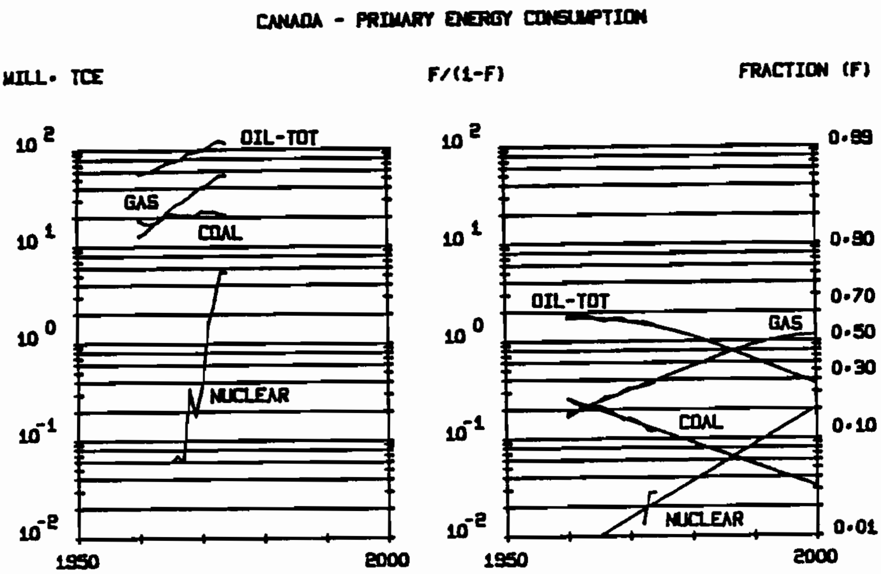


The primary energy substitution for the UK is repeated here using OECD data. In spite of some discrepancies with other data sources, the predictions differ only in relatively small details from those on page 36. Even if nuclear should penetrate the market more rapidly, it would produce only a small dent in the dominance of gas during the next several decades.



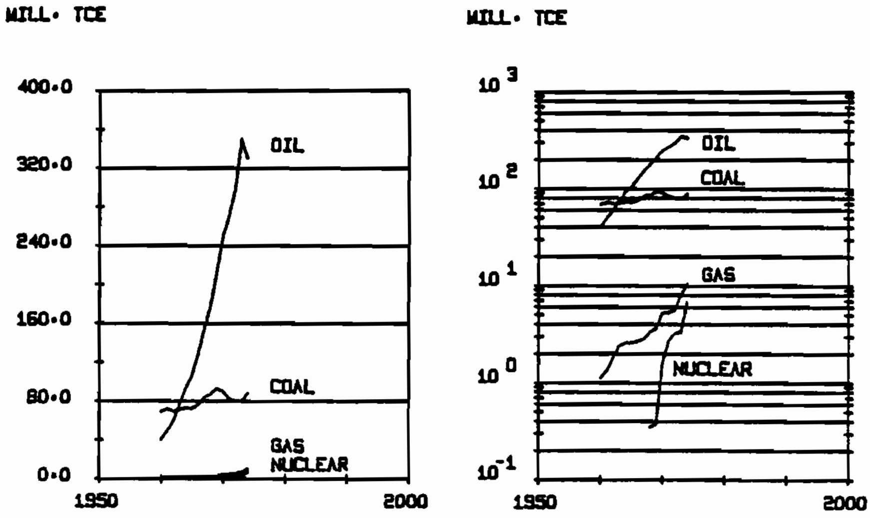
The primary energy consumption (left) and substitution (right) for Italy are shown here with a 15-year OECD data base. The penetration of nuclear energy (10 percent by the year 2000) is hypothetical and based on the assumption that Italy will not be very different in that respect from other European OECD countries.

The future appears very bright for gas to reach dominance in the next decade. Although this is supported by the efforts to link Italy with the Netherlands, the Soviet Union, and North Africa, via a pipeline under the Mediterranean, it is certainly beyond the rosiest plans of the gas industry. If we assume that gas growth was "forced" up to 10 percent and consequently fit the logistic with later data, and set nuclear penetration (improbably) as fast as gas, we reach a more acceptable but not very different conclusion.

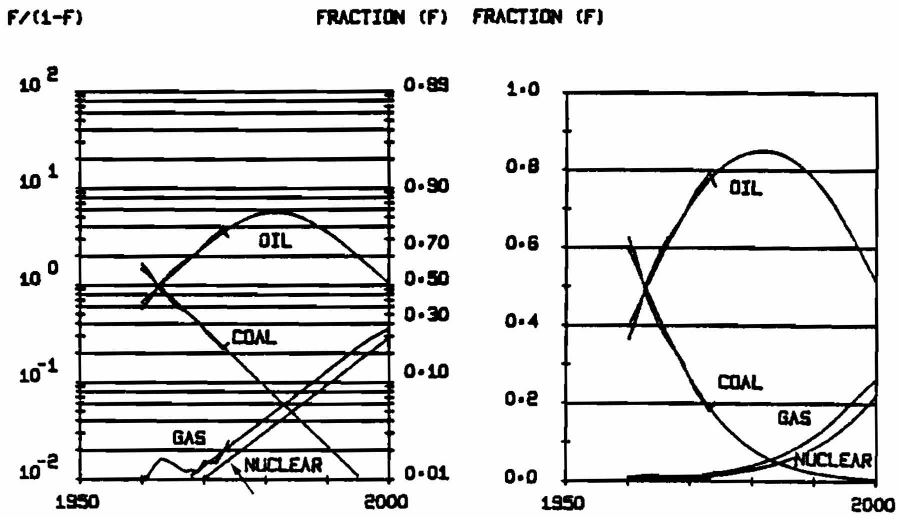


The primary energy consumption data for Canada do not show any particular pattern, except a very fast inroad of nuclear energy, although at a relatively low level. The logistic analysis reveals extremely smooth transitions, much similar to those of Austria, with time constants on the order of 70 to 80 years. In spite of Canadian devotion to nuclear energy, we drew a prudent scenario, assuming about 16-percent nuclear in the year 2000. As in most of the world, gas appears to peak and become dominant in the year 2000.

JAPAN - PRIMARY ENERGY CONSUMPTION



JAPAN - PRIMARY ENERGY SUBSTITUTION



The primary energy consumption data for Japan are taken from the OECD and cover the period 1960 to 1974 for coal, oil, natural gas, and nuclear; they are all expressed in millions of tons of coal equivalent (tce). The oil data include consumption of crude oil and petrochemical products. Nuclear is just beginning. Today there are 20 GW(th) of installed capacity (IAEA 1977), amounting to about 2 percent of primary equivalent.

In spite of Japan's unique situation as a country with very large, recently developed industry linked to an almost complete dependence on imports, the primary energy substitution shows nothing very unusual. *Coal* is being replaced by oil, a trend begun after World War II that appears to end in the nineties. The dependence on oil is fundamental, but only a little higher than that of France and similar to that of Italy. Oil starts to saturate now, as the equations could have predicted (using data before the oil crisis!). According to the equations, oil should be phased out around 2030, much later than for France or Italy.

Gas enters the scene somewhat late, at the end of the sixties, perhaps because it has to be imported using the complex technology of LNG. Perhaps for the same reason it does not seem to play the same central role as in Europe or the United States. According to the equations, it should peak around the year 2010, in consonance with the world peak.

Nuclear is fairly hypothetical, although we have tried to use the various forecasts prudently. The isolated point near gas (see arrow) indicates the actual situation. With nuclear penetration reaching 10 percent in the nineties, the rate coincides with that of other fuels. Nuclear would then become dominant during the first half of the next century, even if a new source is introduced around the year 2000.

Today there are 20 GW(th) of installed capacity (IAEA 1977), amounting in terms of primary equivalent to more than a 2-percent share. Additional plants with a total installed capacity of 27.6 GW(th) are under construction and should be in commercial operation by 1982. Another 14.7 GW(th) are planned to be available by 1984 (IAEA 1977). Assuming that the long-term energy consumption growth prevails during the next decade and that the utilization factor is 75 percent, we project a nuclear share of about 7 percent by 1984. Our scenario of the long-term nuclear penetration rate assumes that licensing and political and construction problems will lead to delays. Thus, we predict a 7-percent share 4 years later in 1988.

At the turn of the century, oil, gas, and nuclear appear to share the market equally, which implies an extraordinary advance in the technologies of transporting natural gas (or some derived products?) overseas and a virtual saturation of the electricity market by nuclear power stations.

ACKNOWLEDGMENTS

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SOLAR OPTIONS IN CENTRAL EUROPE
A Synthesis of Solar Technology Assessment and Contemporary Criteria in 1978–1979

Charles R. Bell

PREFACE

Evaluation of solar energy as a potential substitute for fossil fuels and identification of the time phase in which solar technology may become a significant part of the energy supply mix are constrained by the characteristic uncertainties of solar energy inputs, the developmental status of solar technology, and the evolution of other energy supply alternatives. The numerous variables within the spectrum of attainable solar energy conversion performance allow a variety of approaches to the assessment of its utility. This interim effort identified the options that are now (1978–1979) most viable for solar energy exploitation in Central Europe, and the economic, as well as technical parameters of these options. In spite of the large number of contemporary concepts for the use of solar energy, a correlation with prototype data was made wherever possible to maximize the usefulness of the results. Nevertheless, the rapidly advancing research and development in solar technology, and the possibilities of significant breakthroughs in energy conversion and storage, necessitate the qualification "interim study" as an overall descriptor for this work.

The known history of engineering and industrial progress manifests the real potential of mass production, where there is objective and competent management, as well as favorable markets. The diffusion of solar technology will require a much more careful, well-coordinated effort from research, development, industrial, and governmental institutions, because it is unlikely to win a strong marketshare on its own. If left to the "forces of the free market," it may not attain the timely level of diffusion envisioned as a prerequisite for its becoming a significant element of the future energy supply mix. The fact is that the attainable performance of solar energy may be marginal in some geographic areas and locations, unless the

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collection, conversion, and storage are optimized in terms of durable efficiency, performance, and economic effectiveness. Even a superficial review of the collector area requirements for providing a modest solar energy diffusion shows the need for a well-coordinated, continuing overall optimization effort.

Regrettably, a large volume of research work in the energy field lacks critical review in terms of technical or economic feasibility in the given time phases and with regard to the regional characteristics. The limited resources for the effort reported here did not permit a systematic validation of the data – their selection is based on availability, years of engineering experience, and the judgment of the author.

SUMMARY

The contemporary (1978–1979) state of the art of solar energy conversion technology offers merely a limited view of the long-term potential of solar options in Central Europe. Nevertheless, the principal criteria are well enough understood to allow identification of the prerequisites for an accelerated use of solar systems for supplying thermal energy, as well as for electric power generation.

The global insolation (direct and diffuse solar radiation) for Central Europe ranges from about 1,000 kWh(t)/m^2/yr near latitude 50° N, to nearly 1,300 kWh(t)/m^2/yr near latitude 45° N. Considerable climatic fluctuations, pollution caused by urban and industrial concentration, and topographic influences contribute to the wide variety of uncertainties about solar energy inputs. Typical values are identified for comparative analyses. The potentially viable solar options have been analyzed in four categories:

1. Residential space and water heating systems (low-temperature options, <100 °C), using a variety of nonconcentrating, fixed flat plate collectors with heating oil substitution capacity of about 30 to 50 liters/m^2/yr (depending upon the economically justifiable working fluid storage capacity). The average (1978–1979) cost of such retrofits ranges from \$200/m^2 to 600/m^2 of installed systems (depending upon performance, quality, and installation difficulties of the hardware). Well-coordinated programs, leading to the integration of solar systems with other energy-saving measures, can significantly reduce their cost, while improving their performance.

2. Agricultural and moderate-temperature industrial process-heat-generating systems could use a variety of collectors ranging from nonconcentrating (fixed) to concentrating sun-tracking collectors. This choice of equipment depends upon the temperature requirements (>100 to 300 °C). Such area of application has a large potential but requires a systematic survey of many industries, which was beyond the scope of the work reported here.
3. *S*olar–*t*hermal–*e*lectric *c*oncepts (STEC) (high-temperature options, >400 °C) for generating electric power, and possibly hydrogen, in regions with favorable insolation, using high concentration by sun-tracking collectors (heliostats). System cost estimates for the 1990s for mass-produced hardware range between $1,700 and $2,200/kW(e) (1978 US$), without energy storage. This high-technology category is especially suitable for developing export and compensation trading.
4. Photovoltaic systems (fixed-angle arrays) for generating electric power, capable of converting direct and diffuse solar radiation, may become competitive with thermal systems after 1990, if the technology progresses at the same pace as in 1978–1979. System cost estimates for the 1990s (in favorable insolation regions) are between $1,500 and $2,400/kW(e) (1978 US$), excluding energy storage. For example, hydrogen could become the needed storage medium.

Parametric data and trade-off possibilities are offered to provide foundations for preliminary estimates of quantitative criteria, leading to the future contribution potential of solar options, both in the European region and in areas of higher solar insolation, where the proposed compensation trading concept (import/export) could be instituted.

The future, integrated versions of solar options could support the delineation of long-term energy policies, ultimately leading to the disengagement of energy demand from economic growth. This would be attainable by the next generation of industrial equipment and residential buildings, which will maximize the use of regenerative energy sources, subsequently decreasing the consumption of conventional energy carriers. It would include the intensified recycling of most materials, and, in particular, of those used to construct solar systems, thus drastically reducing the energy investment in the materials of intensive solar hardware. A variety of interrelated standardization and energy management measures for improving the overall cost effectiveness of solar options is considered as a prerequisite for solar options in Central Europe.

A conceptual evolution of a single-family house is shown in this report as a reference case for integrated solar energy systems, both active and passive, together with the use of heat-pumps and heat recovery from waste water, as well as from ventilated air.

A series of recommendations include the need for hardware standardization; the use of mass production methods; the need for development of more competitive energy storage; the structuring of national familiarization programs, and a formulation of a broad variety of incentives.

The synthesis of all these measures ought to serve as a stimulus to further systematic development of solar options.

INTRODUCTION

The critical aspects of solar technology are still in the developmental process, the outcome of which is uncertain because of the large number of technical and economic variables affecting the application of solar options. Nevertheless, it is useful to evaluate what the justifiable rate of application of solar policy options is, which causes solar to be a growing contribution to the future energy supply mix. This is especially true when there is concern with an orderly long-term transition from nonrenewable, and often polluting, energy sources to a renewable, and cleaner, energy era.

The intermittent nature and the relatively low density of solar energy requires the use of large collector areas, which necessitates capital- and material-intensive collection, conversion, and storage systems. Unless a careful optimization of the design, orientation, and selection of a suitable solar system for a given requirement and location is made, its performance will be, at best, disappointing. A premature large-scale application of solar technology can be just as undesirable as a late implementation. For a highly industrialized region, such as Central Europe, a premature large-scale application of solar technology means using retrofit solar installations which are not likely to attain the performance and cost effectiveness of well-integrated solar installations in the next generation of buildings and industrial facilities.

A successful timing for an intensified use of solar options depends on further progress in the applicable research and development areas, and on the attainability of a competitive status with other energy supply alternatives in the future. While the desired technology assessment is currently constrained by the developmental status of solar technology, as well as by the uncertainty of the availability of petroleum and its future price, the contemporary criteria have been evaluated to provide a view of the potential of solar options in Central Europe.

SOLAR ENERGY AS A RESOURCE IN CENTRAL EUROPE

Existing meteorological data in Central Europe are merely a broad indication of solar energy as an applicable resource. Only a few meteorological stations have made measurements that can be directly applied for identification of the actual usable components of solar insolation.* The available global insolation data, direct and diffuse, must be adjusted to the local weather patterns, altitude, proximity to mountains or large bodies of water, air quality, shadowing effects (losses of illumination during early and late hours), as well as wind and humidity effects. The values vary by day and by location. In specific assessments for a given site, a stipulation of 20 degrees minimum elevation of the sun, to reduce shadowing effects, may significantly decrease the annual number of useful sunshine hours (i.e., to less than 1,100 h/yr near the Alpine regions, or to below 900 h/yr in the northern regions). This means that the annual capacity factor of a solar energy conversion system using (sunshine) concentrating collectors (to obtain higher temperatures) is less than 0.12 near the Alpine regions and 0.10 in the north, compared to fossil fuel systems, which can attain 0.70 or more.

To illustrate some typical insolation values for the Central European area, Table 1 offers averages of global insolation for latitudes 40° N and 50° N, both inland locations, arranged by seasons. It is rather obvious that most of the available solar energy is in the summer months, when less is needed except for industry and agriculture.

A review of insolation averages for the Federal Republic of Germany (FRG) revealed an average of 1,000 kWh(t)/m^2/yr and 1,650 hours of sunshine per year of which only 1,000 h/yr may be useful for conversion to a higher-temperature process heat (i.e., 150–300 °C). Furthermore, the typical specific heat demand for existing single-family houses ranges from about 150 kWh(t)/m^2/yr for a terraced house (about 100 m^2), to nearly 400 kWh(t)/m^2/yr for a separate standing house (about 120 m^2) exposed to the elements of the weather. Most of the heating is required for the winter months, and some is required during the transitional months, calling altogether for about 1,700 h/yr. Comparison of these values with insolation data for the winter and transitional months (Table 1) points to the importance of energy storage (hot water storage); the energy demand is highest when the solar energy inputs are the lowest.

*Since 1976, an effort has been in progress to improve this situation.

TABLE 1 Sample values of insolation on horizontal surface in European areas.

Latitudes	Time of year Four winter months: Nov., Dec., Jan., Feb. (= 120 days)	Four transitional months: Mar., Apr., Sept., Oct. (= 122 days)	Four summer months: May, June, July, Aug. (= 123 days)	Annual totals (= 365 days)
50° N				
kWh(t)/m^2	130	360	600	1,090
%-year	12	33	55	100
Sunshine h/yr	230	580	780	1,590
%-year	14	36	50	100
40° N				
kWh(t)/m^2	280	520	880	1,680
%-year	17	31	52	100
Sunshine h/yr	490	770	1,000	2,260
%-year	22	34	44	100

It is characteristic in Central Europe that about a half of the insolation is diffuse. Evaluation of solar energy as a resource must therefore include a representative range of solar insolation for the various cloud covers. Table 2 provides an overview of such estimates.

Low-temperature solar systems and photovoltaic systems use both direct and diffuse radiation which make them potentially suitable for application in Central Europe. Solar energy conversion systems for moderate and high temperatures require concentrating collectors that function only during direct sunshine.

A correlation of Tables 1 and 2 together with realistic conversion efficiencies (see Table 3) provides a foundation for estimating the attainable performance of solar energy as a resource in Central Europe.

OVERVIEW OF THE SELECTED SOLAR ENERGY CONVERSION OPTIONS

An analysis of the 1978–1979 state of the art of solar technology yielded numerous concepts, representative samples of which were used as theoretical reference systems for the evaluation of the potentially suitable solar

TABLE 2 Range of typical solar insolation densities for various cloud covers.

Weather conditions	Daylight insolation densities (~kW(t)/m^2 on horizontal surface)
Heavy clouds, no sunshine, all radiation diffuse	0.10–0.25
Light clouds, no sunshine, most radiation diffuse	0.25–0.45
Hazy sunshine, most radiation direct	0.45–0.75
Clear sunshine, all radiation direct	0.75–0.90

options in Central Europe. Four categories of solar options were selected for interim technology assessment:

1. *Low-temperature options* for water and space heating (operating temperatures below 100 °C) in residential, commercial, and public buildings.
2. *Moderate-temperature options* for production of industrial or agricultural process heat (operating temperatures between 100 and 300 °C), or for the absorption type of air conditioning.
3. *High-temperature options* (operating temperatures in excess of 400 °C) as solar-thermal-electric-concepts (STEC); and possibly for hydrogen production.
4. *Photovoltaic options* for direct production of electricity and possibly for hydrogen or synthetic fuel production.

Categories 1, 2, and 4 were evaluated for application in Central Europe; and categories 2, 3, and 4 for development as potential export items and instruments for future compensation trade.

Solar technology is in various stages of development and with the exception of category 1, the existing hardware is essentially experimental, or in some cases first generation prototypes at best. This means that most performance and cost information is subject to further improvements. A composite of *projected performance and cost estimates* was used, selecting concepts of promising characteristics supported by theoretical and empirical information, to produce an overview of the reference systems. Table 3 features a comparative assessment of the selected options for the insolation regions of Central Europe, and for favorable insolation regions that are representative in some of the developing countries. The range of estimates illustrates uncertainties in design features, selection of materials, and other variables. Neither large scale energy storage nor hardware and labor transportation were included because of the associated complexities and uncertainties (particularly for remote sites in desert and mountain regions). .

In order to project a reasonably realistic capital cost structure, mass-production methods used in the automotive industry were considered representative of the lower limit of learning curves. Approximations with automotive products (European economy-class automobiles) showed a production cost average of \$3.50/kg hardware, or in terms of retail cost about \$6/kg hardware. These relate to the production of about 1.4 million complete automobiles per year (Volkswagen production is about 9,000 units per day, or 2.5 million complete units per year). It is estimated that nearly 20 years would be required to attain the desired target cost, without causing major capital and materials availability diversions, if ~85 percent learning curves are assumed.

Examining Table 3, with due consideration of the uncertainties, the overview indicates that the energy payback time favors mainly the low-temperature options and, to a lesser degree, the photovoltaic options for the insolation levels of Central Europe. If the recycling of materials is properly organized, the energy payback time can be drastically reduced. The photovoltaic options are still speculative when considering cost reduction feasibility. The capital payback time could become relatively favorable in most cases, except for STEC, in the low-insolation regions. This is primarily due to the limited amount of useful sunshine hours in Central Europe.

The low-temperature options can be installed as retrofits in existing buildings, or as integrated systems with heat-pumps and heat recovery equipment in the low-energy-demand houses of the future, the latter being decisively a superior alternative.

A future design of *a low-energy demand, single-family house* may incorporate a number of features separate from solar systems in contrast to conventional building practices, as summarized in Table 4. Although the attainable energy savings must be evaluated separately for each case and location, an integrated design of a low-energy-demand house may reduce the energy demand to less than 25 percent of that for a conventional building, i.e., one constructed prior to 1978. In favorable locations, this may eliminate conventional backup heating systems and allow the use of simple electric heaters in hot water storage tanks. This would facilitate optimized energy management in urban areas and reduce the sources of air pollution.

Further delineation of the criteria is contained in the description of each option.

TABLE 3 Overview of the estimated characteristics of selected solar options.[a]

Estimated parameters	Solar energy conversion systems					
	Global insolation ~1,000 kWh(t)/m²/yr Rated insolation ~0.48 kW(t)/m²			Global insolation ~2,300 kWh(t)/m²/yr Rated insolation ~0.76 kW(t)/m²		
	Low-temperature retrofits	High-temperature daylight STEC	Photovoltaic daylight arrays	Low-temperature retrofits	High-temperature daylight STEC	Photovoltaic daylight arrays
Energy storage	~6 m^3 hot water	~4 h storage	without storage	~6 m^3 hot water	~4 h storage	without storage
Collector area (~m^2/kW)	6	21	16	3	8	13
Overall system efficiency (annual)	0.35	0.10	0.13	0.45	0.17	0.10[b]
Use	Space and water heating	Electricity and synthetic fuels		Space and water heating	Electricity and synthetic fuels	

Direct system cost (~$/kW (1978 US$))[c]	1,200 to 3,600	4,500 to 5,800	1,850 to 2,950	600 to 1,800	1,700 to 2,200	1,500 to 2,400
Energy investment (~MWh(t)/kW)	7.3 to 12.0	21.00 to 52.00	18.50 to 24.60	3.6 to 6.0	8.0 to 20.0	15.0 to 20.0
Attainable primary energy substitution (~tce/kW/yr)	0.15 to 0.24	0.36 to 0.42	0.20 to 0.26	0.30 to 0.40	0.96 to 1.20	0.30 to 0.38
Energy payback time (~years)[d]	3.7 to 10.0	19.00 to 55.00	8.6 to 14.7	1.1 to 2.4	2.4 to 8.0	4.8 to 8.3
Operational availability (~year)	1979	1995	1995	1979	1995	1995

[a] Configurations based on average insolation ratings for the given regions and on realistic load factors (i.e., ~1,700 h/yr for the low-temperature retrofits). Selected reference systems dimensioning was used.
[b] Decreased efficiency due to higher operating temperatures.
[c] Estimates for the year of operational availability.
[d] Prior to recycling (all subject to choice of materials). Not including site preparation, transportation to site, labor accommodation and other indirect energy investments, depending upon the location.

TABLE 4 Attainable energy savings for single family houses of modified design, as compared to conventional houses.

Energy-saving features	Examples of attainable energy savings[a] (percent)	Typical energy payback time[b] (years)
Optimized house insulation	35–45	0.3–0.5
Passive solar system	25–35	undetermined[c]
Solar water heating (including storage)	8–12	2.0–5.0
Solar space heating (including storage)	40–60	4.0–8.0
Heat-pump application	25–30	0.6–1.5
Heat recovery from exhaust air and waste water	15–30	undetermined[c]

[a] Not cumulative.
[b] Subject to choice of materials.
[c] Subject to building design and use.

LOW-TEMPERATURE SOLAR OPTIONS

Low-temperature solar-thermal systems are the closest to accelerated, large-scale commercialization. To aid the diffusion process in Central Europe, unified standardization and quality control regulations are needed to secure the availability of fitting spare components, such as collectors and hot water storage tanks.

Two reference systems were formulated for the interim assessment of the rate of possible application of such options:

1. A solar water heating system (retrofit), with 8-m^2 collector surface, for a single-family house. Such a system can substitute for oil heating of the water in the order of about 1,000 liters oil/yr, because of the otherwise marginal efficiencies of oil heating systems during the summer and transitional months.
2. A solar space and water heating system (retrofit), with 35-m^2 collector surface, for a single-family house. Such a system can substitute for oil heating in the order of about 1,540 liters oil/yr.

Using statistical information from the FRG, a representative assessment of both single- and two-family houses was made to estimate the number of solar systems that could be installed. About *3.2 million* of such buildings in the FRG could be adapted for a *solar system by the year 2010.* The primary energy savings attained annually by such a measure would be about 11 million tce*, or about *1.5 percent of the estimated primary energy* at that time period. A substantial amount of the installed solar systems would have to be retrofits, because the projected growth rates of suitable new buildings are not high enough to concentrate only on the advanced, integrated low-energy-demand buildings. However, such new building designs would eventually foster optimum savings of fossil fuels, and optimum benefits from environmental considerations.

Figure 1 conceptualizes a version of the transition from fossil fuels to the maximum use of solar energy and electric power in the FRG. Nearly four million residential units would be involved during an estimated 75-year period. This would contribute to the reduction of pollution, while facilitating the use of synthetic fuels in central power plants. It ought to be realized that between 25 and 40 million m^2 of collector surface are required in Central Europe to substitute (collectors) for 1 million tce of primary energy, depending upon the selected design features and economic trade-offs. The direct (solar systems) cost for 1 million tce is estimated to be between \$5 and 24×10^9 (maximum rate \$2 to 6×10^9 per year) depending upon the chosen trade-offs. The indirect cost for the integrated systems may be absorbed in the building cost. A program of such magnitude becomes interesting as petroleum prices increase and as economic losses, due to pollution, are fully recognized and quantified.

An assessment of the contemporary technical and economic criteria is necessary to identify the evolution potential of solar options from retrofit installations to the fully-integrated versions. Table 5 shows examples of prices of solar-specific hardware, such as would be used in the selected reference systems, as offered on the FRG market in the 1978–1979 time period.

An installed retrofit representative reference system for *solar water heating* (8-m^2 collectors) was priced in 1978 at \$3,800; with the long-term cost reduction projected to be \$2,400, when large-scale mass production prevails. A lower cost will be realizable for fully integrated systems included in the design of new buildings.

An installed retrofit representative reference system for *solar space and water heating* (35-m^2 collectors), was priced in 1978 at \$21,000, but some integrated versions of the same system were offered in 1979 for \$12,000; the long-term cost reduction was projected to be \$7,000, when large-scale mass production and full design integration prevail.

The long-term cost reduction projections correlate reasonably well

*tce = tons of coal equivalent (1 tce = 8140 kWh(t)) ≈ 4.8 bbl (crude oil).

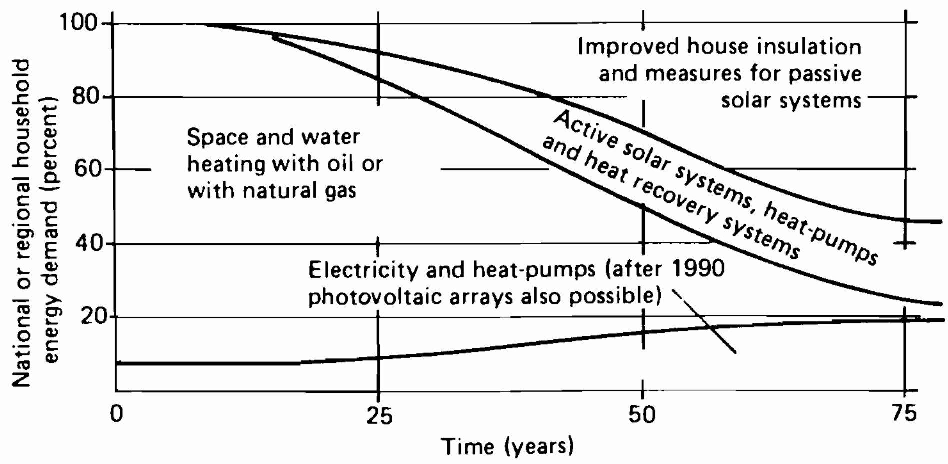

FIGURE 1 Possible evolution of low-temperature solar applications for residential buildings.

with the cost of automotive hardware. The prices of solar specific components represent nearly 50 percent of a typical retrofit space and water heating system installation; about 25 percent is for "off-the-shelf" hardware, and the remaining 25 percent for transportation, assembly, installation, and retrofit design. In the integrated systems of the future, the collectors will be a part of the roof, forming a part of the insulation, and many of their features will be standardized, proving to be more cost effective as indirect costs will be absorbed in the building costs. Furthermore, material recycling will also contribute to the reduction of energy investment and possibly to cost reduction.

Figure 2 illustrates the performance of various solar energy collector designs when traded off against costs of the reference systems for space and water heating. The designs without a selective absorber surface do not generally give a satisfactory performance when diffuse solar energy prevails. The principal constraining factors are the conversion of diffuse solar energy and the cost/performance capacity of hot water storage; they do not permit cost-effective seasonal storage. Thus a high percentage of solar energy collected during the summer and, to a lesser degree, during the transitional months is lost (see Table 1). This is limiting the heating-oil substitution performance of such systems in Central Europe. The graph also implies that cost/performance trade-offs are necessary for each application and location to optimize a system. For an average system, at a cost of \$350/m^2, the corresponding annual substitution, or savings, of heating oil is about 45 liters; in August 1979, this was about \$12/m^2/yr, without con-

TABLE 5 Price ranges of quality solar energy hardware in the FRG (1978 US$).

Hardware (not installed)	Components' price range ($)	Average price ($)
Single-glazed collectors without selective absorber surface	120–240/m^2	144/m^2
Double-glazed collectors with selective absorber surface	134–288/m^2	168/m^2
Hot water storage tanks		
3–6 m^3	720–1,440/m^3	960/m^3
7–30 m^3	384–624/m^3	480/m^3
Control units	336–960/unit	576/unit

sideration of maintenance costs. The amortization time would obviously be extensive even if the life of a well-constructed system could exceed 30 years. However, large-scale mass production of the systems should reduce the cost to about $180/$m^2$ and the increase of heating-oil prices will eventually facilitate a more favorable cost effectiveness. The cost of long-term financing is not included in these estimates. More important, however, is that the decision process must be based on a life-cycle cost, yielding the benefits of fuel savings, rather than on an acquisition cost.

The conceptual evolution of a single-family solar house is shown in Figure 3, integrating the energy-saving features, identified in Table 4, with a large-scale energy management potential, illustrated in Figure 1. Optimum insulation is taken as a prerequisite, as is floor or wall heating that can function with working-fluid temperatures below 30 °C. Heat recovery from waste water and exhaust air, and heat-pump integration with the solar system, are viewed as the optimum long-term alternative.

The application of passive solar systems is in an early developmental stage, but their performance in prototype houses is indicative of their long-term potential.

MODERATE-TEMPERATURE SOLAR OPTIONS

The production of process heat for industry and agriculture is in the early developmental phase. Nearly 25 percent of primary energy for industry is used for process heat below 300 °C, indicating a potential utilization of solar energy for either preheating, to save fuel, or for direct conversion to process heat. The process-heat demand has two major categories:

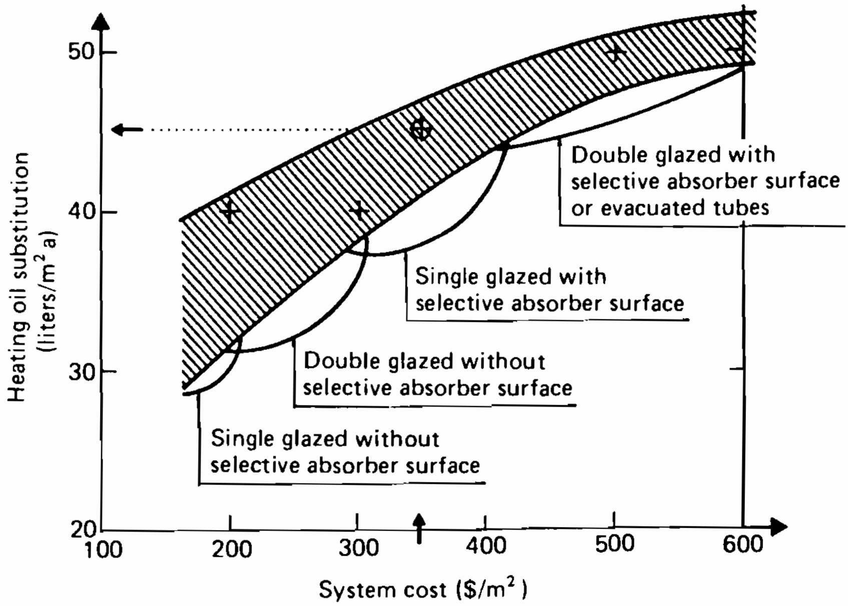

FIGURE 2 Heating-oil substitution potential of various collectors with the referenced solar space and water heating system.

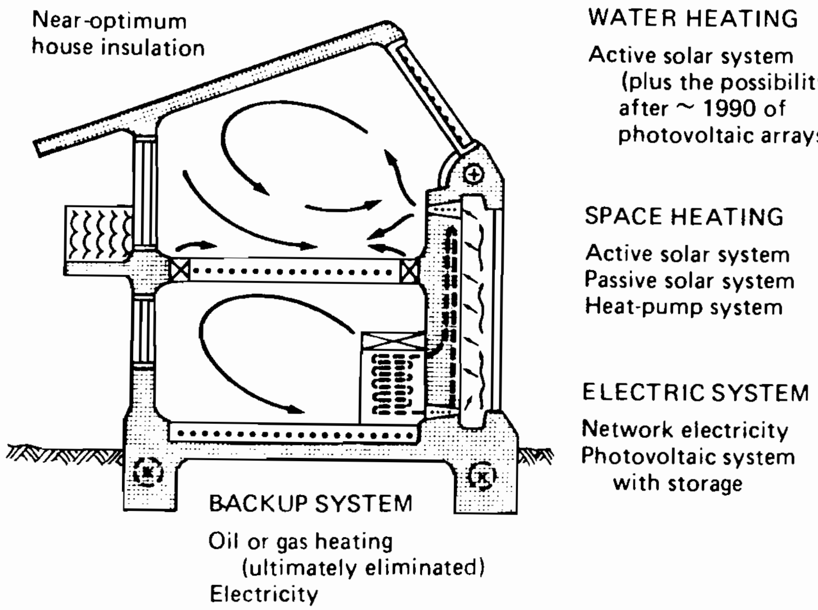

FIGURE 3 Evolution of solar house options.

1. *Hot water for*:
   Chemical industry
   Textile industry
   Cleaning and washing facilities, and many others
2. *Hot air for*:
   Drying (agricultural products, lumber, food, etc.)
   Dehydrating
   Industrial processing, and many others

The direct use of collected solar energy, without storage, may prove attractive enough, in some applications, for integration in the next generation of industrial equipment. The cost would be near the collector cost shown in Table 5.

Moderate-temperature solar options can provide air conditioning, small-scale electric power generation, and other related functions. The rationale offered for the low-temperature options is applicable here. Mass-production of collectors and storage systems, approaching the methods of the automotive industry, will ultimately open new opportunities for the use of moderate-temperature solar options.

HIGH-TEMPERATURE SOLAR OPTIONS

The interest in *high-temperature* solar technology in Central Europe is motivated by export possibilities. A range of medium- to high-temperature concepts, from a high-performance flat plate collector system to heliostat fields and a central tower receiver, were evaluated for generating electricity and manufacturing synthetic fuels in arid areas (insolation about 2,300 kWh(t)/m^2/yr and 2,500 hours of usable sunshine per year). The principal criteria for the most promising STEC concept (heliostats and a tower) are shown in Table 3. Estimates indicate that the electric power generating cost for commercial versions of 100-MW(e) daytime power generating plants may be about US$0.12 to 0.16/kWh(e), with operating and maintenance costs accounting for nearly 10 percent, because of the large mirror surfaces and the numerous tracking subsystems.

Paraboloidal dish systems may prove suitable for hydrogen production via a thermochemical cycle, which could attain an overall systems efficiency of ~25 percent, *if current projections are realizable*. The capital cost for a commercial version of this concept is estimated at $1,400/kW for hydrogen gas production, or about $1,750/kW for the production of liquefied hydrogen (LH_2), storage not included.

Two-dimensional troughs could prove useful in areas with favorable insolation, to deliver higher-grade process heat, electricity, air conditioning, or even hydrogen. With a capital cost estimate at $2,000/kW (rated, without energy storage), the cost of electricity would probably be $0.16/kWh(e), including operation and maintenance costs.

Conceptual and prototype efforts are sponsored in the USA, aiming at 100 MW(e) STEC (heliostats and a tower) with 420 MWh(e) storage capacity. The prototype's direct cost ranges from $13,000 to $15,000/kW(e) for current (1978–1979) constructions.

Baseload configurations of such plants would require large-scale energy storage, either of a pumped hydro category for about $320/kW (rated), or thermal storage for about $430/kW (rated).

Most of the information on STEC concepts is still too speculative for the long-term projection of their large-scale use. Furthermore, it ought to be realized that the indirect cost must be added to the direct cost, which may increase the capital requirements for STEC systems by 70 percent or more, depending upon the remoteness of the site, the access to it, and the overall logistics. In the case of conventional electric power plants, the indirect cost has been up to 50 percent of the direct cost – a trend that is increasing with demands for better environmental protection.

PHOTOVOLTAIC OPTIONS

The versatility and the promise of development trends of photovoltaic systems indicate that if the cost-reduction objectives are met, photovoltaic arrays may become competitive with solar-thermal systems before 1995.

The long-term objective of the US Department of Energy calls for the reduction of the direct cost to $500/kW(e) peak for photovoltaic arrays. This could yield systems cost in high insolation regions ranging from $1,600/kW(e) peak for residential sizes (~10 kW), to $1,800/kW(e) peak for small-size electric power generators (~500 kW), and perhaps as low as $1,500/kW(e) peak for large, central stations (~100 MW). The added indirect cost depends upon the location, access, preparation, and logistics. In the case of residential buildings, it could be absorbed in the building costs. But even $2,000/kW(e) would become reasonably competitive, if the relatively high system efficiencies are obtained. For example, the combination of gallium arsenide (GaAs) and silicon (Si) or cadium sulfide (Cds) cells to capture a broader range of radiation spectrum, and the use of concentrators, may produce system efficiencies of nearly 30 percent.

Because the photovoltaic systems utilize both direct and diffuse solar radiation, and because they do not have to attain thermal equilibrium for effective operation, their application in Central Europe would be very useful.

The multitude of photovoltaic arrays in research and development phase include:

Fixed flat plate arrays
Periodically adjustable arrays
Concentrating arrays (with or without cooling)
Hybrid arrays (with two or more cell materials)

All of these can be used for the production of electricity and hydrogen, and it is the latter which would enhance the feasibility of load leveling and baseload configurations. It will be about 5 to 8 years before the research and development and prototype system phase is completed and the choices among these options are clarified. The desired systems cost reductions may require an additional 20 years of commercial operation when the 85 percent learning curve is assumed. The time it takes will depend upon a rapid increase of market potential for such systems.

INSTITUTIONAL ISSUES

There are numerous legal, administrative, and tax issues that are interfering with the implementation of solar options in Central Europe. These include constraining building codes, tax regulations, absence of quality assurances and the availability of guarantees, and financing problems, all of which vary according to the country and region. National and regional governments must correct such a situation and develop incentives for effective and timely applications of solar options.

EXPORT POTENTIAL

Table 3 shows the representative performance estimates of solar systems in regions with favorable insolation. In large-scale diffusion considerations, the indirect cost associated with the on-site installation of solar technology must be identified with each given region and added to the direct system cost projections, and evaluated in terms of a corresponding life-cycle cost, showing the benefits of eliminating the need for fuel logistics. However, large-scale exports of solar hardware that is capital- and materials-intensive, and thus energy-intensive, should be channeled into the compensation trade (i.e., trading hardware for commodities) mode of operation.

The cost for meeting a basic energy demand that would provide a composite of energy requirements *per capita* in developing countries, where improvement over the bare subsistence level is needed, is optimistically estimated at \$1,500/kW (later this century), with an energy content of about 12 MWh(t)/kW. This composite includes irrigation, water purification, crop drying, initial electrification, and other necessary functions. The risk of exporting hardware with such large capital and energy content would be significantly reduced by the development of an effective compensation trade.

CONCLUSIONS AND RECOMMENDATIONS

When macroeconomics is considered, solar energy conversion technology cannot make a significant contribution to either near-term or mid-term energy supplies; its key potential is in the long-term perspective, characterized by fully integrated solar options and their contribution to environmental progress.

Large-scale implementation of renewable energy systems, e.g., solar energy conversion systems, may require 50 to 80 years for effective large-scale diffusion, depending upon the trends in petroleum pricing, the evolution of other alternate-energy systems and overall energy management. Continuing research and development is expected to produce new techniques for the conversion, transportation, and storage of energy, while increasing and improving the recycling of materials will reduce energy investment in the next generations of both industrial and private equipment. It is too early to formulate a realistic future contribution of solar options for the energy mix of Central Europe. Once current research and development reach a tangible maturity, a more specific technological assessment of solar options will have to be undertaken. Until then care must be exercised to prevent premature commitments in speculative areas. The time for solar options will undoubtedly arrive – the difficulty is to recognize the concept that has the best long-term potential.

In the more immediate future, however, the following measures ought to be given priority:

1. Reduction of solar hardware cost by adapting to mass production processing, together with the standardization of the external dimensions of collectors, and other major components, to facilitate interchangeability and replacements by fitting spares.
2. Formulation and implementation of quality control regulations and facilities to assure the integrity of solar hardware, reduce its maintenance requirements and extend its operational life well beyond the amortization period.
3. Development of efficient and cost effective thermal energy storage systems to maximize the use of solar energy collected during the favorable sunny periods of the year.

4. Development of passive solar energy building techniques, and near-optimum insulation, to facilitate the application of active solar systems, and the integration of heat-pumps.
5. Formulation and implementation of well-coordinated courses and seminars in technical universities and trade schools, to train architects, engineers, and all future builders in the key aspects of the application of solar technology and in the development of building designs which reflect the need to drastically reduce energy consumption.
6. Structuring of national and regional programs, stipulating that all future public buildings and any others financed by public funds (i.e., schools, hospitals, recreational facilities, airports, administrative buildings, railway stations, etc.), should receive priority consideration for the use of applicable solar options. This will increase the knowledge of the emerging technology and its energy saving potential, while stimulating the development of innovative architecture for low energy consumption buildings.
7. Formulation and implementation of *administrative and economic incentives* for the use of solar options by:
   – Creating *tax incentives* for the installation of retrofit and integrated solar systems in residential and commercial buildings
   – Passing "*solar rights*" laws to prevent the future shadowing of solar collectors, both active and passive
   – *Reassessing constraining regulations* and building codes that are jeopardizing the accelerated use of solar options
   – Creating a *comprehensive insurance program* to protect house owners, and institutions willing to provide financing, against premature failure or damage to solar hardware (perhaps with the manufacturers' participation and national support).

These measures would accelerate the acceptance of solar options and aid the development of a mature market for solar hardware, while gradually motivating a sensible transition to an independence from nonrenewable energy sources. It would be advantageous if such measures could be implemented uniformly throughout Europe, or by subgroupings such as the European Economic Community.

It seems appropriate to conclude this summary on the potential of solar options with a quote from the book *The Bankers* by M. Mayer: "The quality of life becomes a function of the energy resources at the disposal of the individual and the capital investment that multiplies his benefits from his efforts. . . ."

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SIMULATION OF MACROECONOMIC SCENARIOS TO ASSESS THE ENERGY DEMAND FOR INDIA (SIMA)

Jyoti K. Parikh and Kirit S. Parikh

SUMMARY

The Energy Systems Program (ENP) at the International Institute for Applied Systems Analysis (IIASA) has developed a set of models giving coverage of energy and energy-related issues for macroregions of the world over the long term (50 to 60 years). The SIMA model, a macroeconomic simulation model to assess energy demand for India, is included in this larger effort, which has been partially supported by a grant from the United Nations Environment Programme (UNEP).

The use of the SIMA model within the energy modeling effort at IIASA reflects the desire to treat the special considerations of developing regions with as much care as possible. In particular, the treatment of the economic profile and prospects of one developing country with this econometric model can lead towards a greater understanding of energy requirements in the face of alternative economic scenarios. The alternative paths selected for use with the SIMA model included a greater intensification of agriculture, increasing aid, and stepped-up investments and exports (to generate high economic growth). The SIMA model focuses on the central issues of capital availability and sources of export earnings for building up the domestic energy sector. Also considered explicitly are the uses of noncommercial energy and the extent and pace of rural electrification characteristic of developing economies.

Further studies that deal with energy problems in developing countries have been and are being carried out at IIASA, in no small part initiated by the SIMA work.

1 INTRODUCTION

This study forms a part of the global modeling exercise of IIASA's Energy Systems Program (ENP). The aim of the ENP effort, in which the world is considered to consist of seven "regions" (Häfele and Basile, 1978), is to evaluate for each region the alternative energy supply strategies consistent with economic scenarios. The ENP defines a world region as a group of countries sharing similar economic features. For this purpose a set of models has been developed, and the models are to be run for each region in the following stages

- Generation of a macroeconomic growth scenario
- Generation of energy demand scenarios consistent with this macroeconomic framework
- Determination of the optimal energy supply mix to meet the energy demand, and consideration of choices of fuel substitution
- Analysis of the impacts on the economy of the selected energy supply mix
- Revision of the macroeconomic framework, if necessary, and iteration of the results of each world region
- Analysis of the global issues concerning energy use and supply

Of the seven regions, four are developing regions, one of which comprises Africa and South and Southeast Asia (excluding Northern Africa, South Africa, Japan, and Asian countries with centrally planned economies).

GENERAL CHARACTERISTICS OF THE AFRICA AND SOUTH AND SOUTHEAST ASIA REGION

Of the main characteristics of the Africa and South and Southeast Asia region, perhaps the most obvious are those of high population growth and limited energy resources. The other characteristics are

- The economy is supply constrained rather than demand driven.
- Agriculture plays an important part in the economy and has increasing capital requirements.
- Imports and foreign aid are of strategic importance in the economy.
- There is substantial use of noncommercial energy (firewood, agricultural waste, charcoal, and animal dung).
- The price elasticity of energy is low, because the present "subsistence" use is at a base level, offering little scope for reducing energy consumption.
- The extent of electrification in rural areas is low; hence demand is suppressed.
- There is competition among the agricultural and nonagricultural (transport, commerce, industry, and services) sectors of the economy for investment and imports.

India constitutes almost 40 percent of the population and 35 percent of the energy consumption of this region, and can be taken as a country typifying the above regional characteristics. For example, in India

- Agriculture forms 45 percent of the gross national product (GNP).
- Noncommercial energy consumption formed approximately 70 percent of the total (noncommercial plus commercial) energy consumption in 1971.
- Only 25 percent of the villages were supplied with electricity in 1971.
- In 1974, 30 percent of export earnings went towards the purchase of oil; at present the figure has risen to 33 percent.
- In the 5-year plan of 1978–1983, 30 percent of government planned investment has been allocated to the energy sector.

Therefore, to understand the behavior of the energy system of the region and its interdependence on the macroeconomic variables, the case study of India is presented as a first step. For this study we have developed a macroeconomic simulation model to assess the energy demand for India – the SIMA model. This model recognizes and attempts to simulate the main features of developing regions that are described above.

Although detailed models are available for each of the stages described in the introductory paragraph, the SIMA model for developing economies goes through the first two (the generation of a macroeconomic growth scenario and energy demand scenarios) simultaneously, so that the feedback from the energy sector to the economy is accounted for as an approximate measure. This may help in reducing the number of iterations required, by providing a more appropriate macroeconomic basis for the ENP set of models.

The SIMA model is used for a long-term period; the projections extend to the year 2030. However, it should be recognized that, even to plan for the energy sector up to 2000, the model should extend much longer, if only to identify approximate trends beyond the planning horizon. The available fossil fuel reserves may easily last until 2000 and beyond, but it is apparent that a shift in energy policy is desirable over the long term. Therefore, a long-term model of this nature is especially relevant for the developing regions whose energy consumption at present is barely above subsistence level. A stabilization of the energy consumption in these regions cannot be foreseen in the next 50 years, if the regions are expected to develop. Projecting the future for the next 50 years calls for a combination of analysis of the past and assessment of the future course of events; the latter will undoubtedly be affected by the economic policies pursued. To explore the policy choices for the future, one needs a mechanism to determine the implications of a given set of policies, and we have therefore constructed a simulation model, the SIMA model.

A BRIEF SUMMARY OF THE WORK ON ENERGY DEMAND FOR INDIA

Projections of energy demand play a crucial role in energy studies. The strategy of supply and the policies pursued to realize the strategy depend on the level of demand. Prior to running the optimization models investigating energy supply options, which are highly refined, the sophistication of these models has to be matched by the projections of demand that drive them. Some of the conclusions of such models can be sensitive to the level of energy demand in an economy. Thus, in the global modeling exercise of the ENP, considerable emphasis is placed on improving the methodology for projecting energy demand. The macroeconomic simulation model of India presented in this report forms a part of this effort. India is taken as a case study of a developing country and it is hoped that the experience gained from using this model will be useful for building appropriate models for other developing regions.

One of the first exercises of energy demand projection for India was carried out by the Energy Survey Committee of India in 1964. This was based on separate trend projections up to 1980 for the household, agricultural, transport, and industrial sectors; these projections were then combined to obtain the total national energy demand. The fuel mix required for the economy was also identified. This exercise, by establishing a data base and a framework for carrying out studies in energy, made an important contribution to the projection of energy demand. It systematically assessed the use of noncommercial fuels, estimated the efficiency of different fuels for various uses, and initiated the use of coal replacement units based on the efficiency of use as well as on calorific content. The use of such coal replacement units rather than coal equivalent units was considered more appropriate in planning for substitution of fuels, particularly of noncommercial fuels by commercial fuels (electricity, coal, oil, and gas). The values of coal equivalent and replacement units are given in Appendix A.

The Fuel Policy Committee of India extended this approach by carrying out projections up to 1990; they also streamlined the data base up to 1971. The Fuel Policy Committee's demand projections were based on more detailed sectoral energy input coefficients, on material balances, and on an evaluation of fuel substitution possibilities.

Parikh (1976), using a similar approach, extended the demand projections up to 2000. Alternative scenarios and strategies are given and the resource requirements for meeting energy needs are also estimated. However, the implications of these cost projections on the development of the economy and on the demand for energy itself have not been investigated.

Parikh and Shrinivasan (1977) have used a linear programming model, within which parts of the energy demand are endogenized, in order to determine India's food and energy options. Demand in the agricultural and transport sectors is prescribed in terms of the desired output of these sectors, such as tons of food grains, passenger-kilometers, ton-kilometers. The energy demand required to meet these needs depends on the technologies selected and is determined within the model, which covers the period up to 2000. However, the authors do not iterate to see whether the final demand projections need to be modified in the light of the techniques and resource requirements indicated by the model solution.

THE OBJECTIVES

The purpose of this report is to project alternative future energy demand scenarios consistent with economic developments and possible energy supply scenarios. It is also to examine the interaction between the increased costs of energy and economic development, which may be important for developing countries where capital accumulation and imports generally constitute the major constraints on development. (The word "demand" is not used throughout this paper in the conventional economic sense of a quantity price schedule. Instead, it refers to the point of intersection of demand and supply, a sense that has been widely adopted by energy analysts.)

When energy is expensive and requires large resources to develop supplies, fewer resources are available for developing other sectors of the economy. Thus, the demand for energy is affected by and in turn affects the development of the economy. The projection of energy demand should be consistent with the projection of economic growth.

Conventional econometric models (for models of India see the references) are usually built for short-term projections. This makes it possible to use linear approximations for nonlinear relationships, which may be locally adequate. A simulation model for long-term projections requires specifications of relationships that are not necessarily linear. With the rather short time series available for India, it is difficult to explore complex hypotheses, and the model had to be kept simple. Relationships that are usually estimated from short-time-series data need to be examined for their appropriateness for long-term projections. In many cases, one may have to replace such estimated relationships by hypotheses that are theoretically more acceptable and that appeal to common sense. At a couple of places we have done so in our model.

In contrast to models of developed economies, in which growth is demand driven and restricted by the limited labor force and by technological progress, models of developing economies have to concentrate on dealing with the difficulties of expanding energy supply, of accumulating capital, and of having a limited availability of imports. The SIMA model requires relatively few exogenous specifications, and we believe it is suitable for coping with the difficulties mentioned above.

Thus, the purpose of this model-building exercise was to construct a model for India that would account for structural changes in the economy; thus, it is built so as to permit an exploration of the effects of alternative scenarios on economic development and energy demand. The scenarios include

- Different levels of government effort to promote investment
- Different rates of development in the agricultural sector
- Different levels of foreign aid
- Different levels of domestic energy availability

Population growth, the level of urbanization, oil price rises, and the capital costs of energy are specified exogenously in these scenarios.

2 THE MODEL

In the SIMA model, the Indian economy is considered as being mainly composed of two sectors. The three essential features of the model can be summarized as follows:

- The two main sectors are agriculture and nonagriculture; the energy sector forms part of the nonagricultural sector but is driven by both of the main sectors.
- The main sectors are in competition with each other for capital stock.
- Some structural relationships are estimated from time-series (1950–1973) data, and others are estimated from scenario specifications.

In the SIMA model the gross domestic product (GDP) is used in private and public (government) consumption and in investment. Private investment is stimulated by government investment and restricted by savings in the economy. Trade is balanced, but foreign aid increases imports and also promotes public investment.

The implications for energy demand and for capital required in the energy sector are derived from the structure of the GNP that emerges. The capital and import requirements for the energy sector compete with the capital and import requirements for the rest of the economy.

In developing a model for long-term projections, the appropriate level of sectoral detail should be used. Although a model with many sectors may permit incorporation of structural changes in some detail, it increases the problems of uncertainties in technological description, and the final projections may be no more reliable than a model with fewer sectors. Although the SIMA model has only two main sectors, it is able to account for structural changes in the Indian economy; some aspects of these structural changes are characterized by the level of urbanization, whose specification in the model is exogenous.

Since one of the features of the model is that it is a useful means of studying the problems of energy policy, the energy sector has to be described in some detail, and the detailed treatment of the energy sector has to match the detail with which the rest of the economy is described. We have tried to resolve this problem by treating the details of the energy sector as consequences of the growth of the economy. The feedback from the energy sector to the economy, however, is based on more aggregated attributes of the energy sector, i.e., the foreign exchange required to import oil and the total investment required for the growth of the energy sector.

A BROAD OUTLINE OF THE MODEL

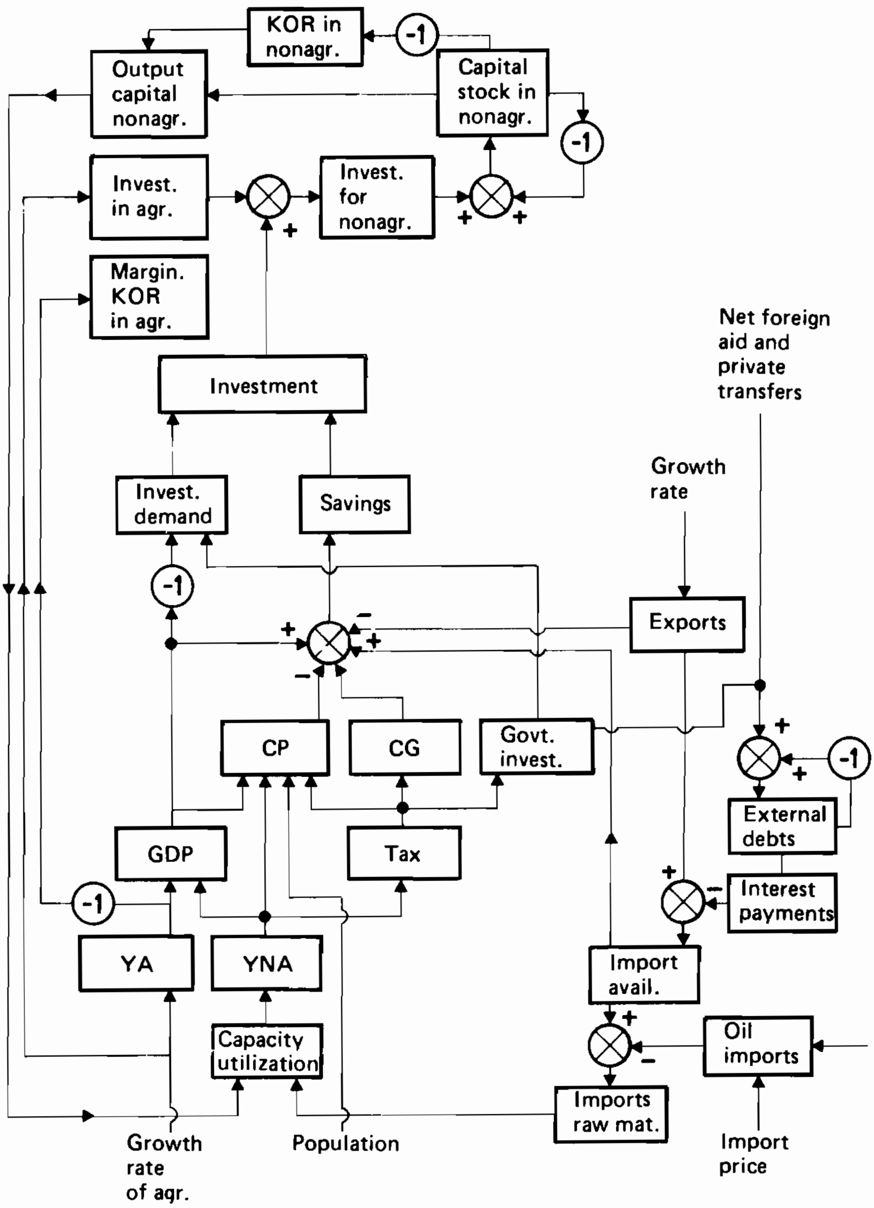
The details of the interactions of the two-sector macroeconomic model can be seen in Figure 1.

The Macroeconomic Module

The GDP is a function of the output of the agricultural and nonagricultural sectors. An exogenously specified growth rate determines the output of the agricultural sector. The output of the nonagricultural sector is determined by the productive capacity created through capital stock accumulation and by the extent to which this capacity can be utilized. Capacity utilization depends on the availability of imports of raw materials, components, and spare parts. The requirements of imports for full capacity utilization depend on the total capital stock and decrease relative to the increase in capital stock, because of the diversification of the economy and import substitution.

Imports are determined by the availability of foreign exchange from net export earnings, by private transfers (from Indians residing abroad), and by foreign aid. The foreign exchange required for importing oil, the price of which is exogenously specified, is first set aside from the total foreign exchange. The remaining exchange is available only for imports of raw materials, spare parts, equipment, and the like.

The GDP generated in the model is utilized for private and government (public) consumption and for investment. Government consumption



GDP	gross domestic product	CP	private consumption	⊗	summation
YA	value added in agr.	CG	govt. consumption	(-1)	lag of 1 period
YNA	value added in nonagr.	KOR	incremental capital/ output ratio		

FIGURE 1 The model structure – the macroeconomic sector.

is a function of the taxes collected, which depend on the output of the agricultural and nonagricultural sectors (the income from each of these two sectors is taxed differently in India). Private consumption, on the other hand, is determined by the per capita GDP after tax, as well as by the composition of the GDP. If agricultural output increases at the same level of GDP, private consumption will increase.

The level of investment in the economy is determined by the demand for and the availability of investment. Government investment, which is determined by the amount of taxes collected and the amount of aid received, stimulates private demand for fixed investment. The level of the previous year's GDP also affects present private demand for fixed investment. Investment availability is determined by the GDP identity. The actual, or realized, investment comprises inventory formation, replacement requirement, net fixed investment in the agricultural sector, and net fixed investment in the nonagricultural sector. Net fixed investment in the nonagricultural sector, obtained as a residual, is added to the existing capital stock of the nonagricultural sector. Since there is a limited availability of arable land, an increased yield per hectare is necessary for agricultural output to be increased. To increase the per hectare yield requires an increase in the capital input to agriculture. Thus, the incremental capital/output ratio in the agricultural sector is taken to increase asymptotically with the level of agricultural output. Conversely, the incremental capital/output ratio in the nonagricultural sector, which is high at present, is expected to decline with the diversification of capital stock and the increased efficiency of capital use. The asymptotic limits of the incremental capital/output ratios are exogenously specified; their behavior is indicated schematically in Figure 2.

The Energy Sector

The structure of the energy sector is illustrated in Figure 3. The total (commercial and noncommercial) energy consumption is related to the level, structure, and characteristics of the GDP and to population. The demand for noncommercial energy is affected by per capita private consumption and by the extent of urbanization. The demand for commercial energy, obtained by subtracting noncommercial energy demand from total energy demand, is divided into electrical and nonelectrical energy. The demand for electrical energy is related to the number of villages that are supplied with electricity. Since the gas reserves of India are insignificant, nonelectrical commercial energy demand is divided into coal and oil, and oil is divided into domestic oil and imported oil. The price of imported

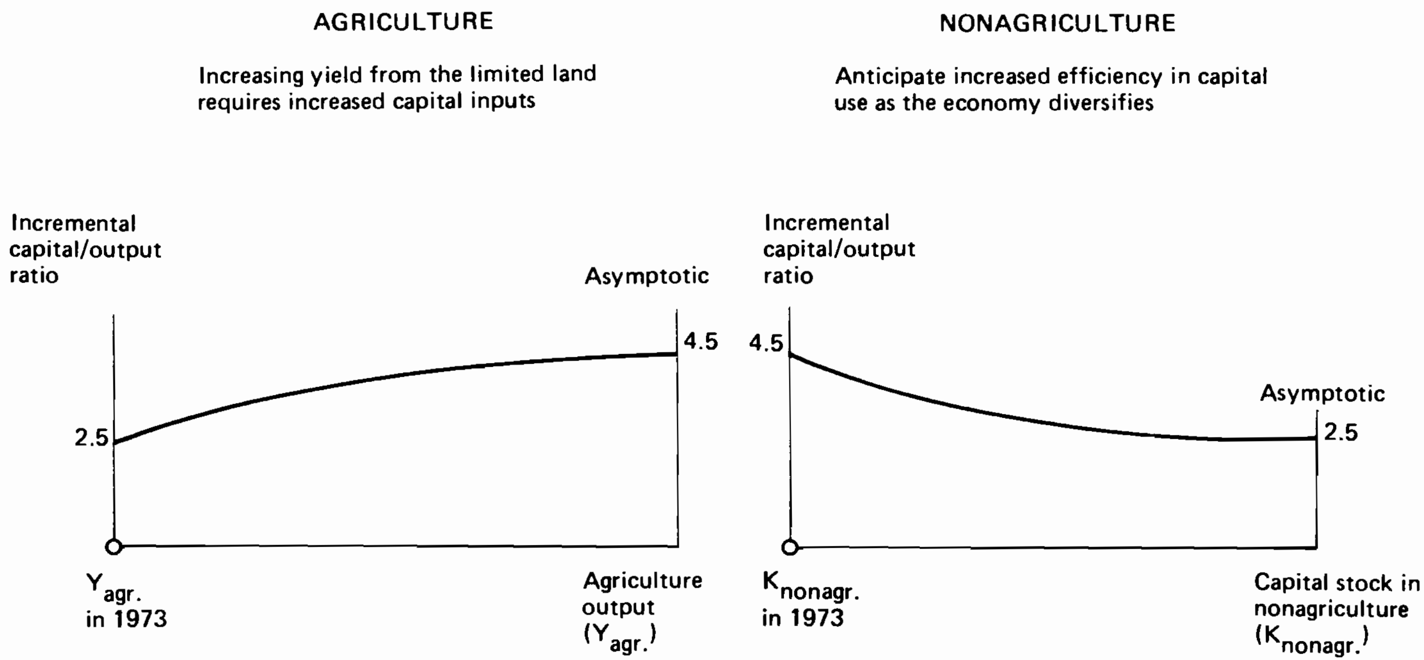


FIGURE 2 Schematic behavior of exogenously specified incremental capital/output ratios in the two sectors of the model.

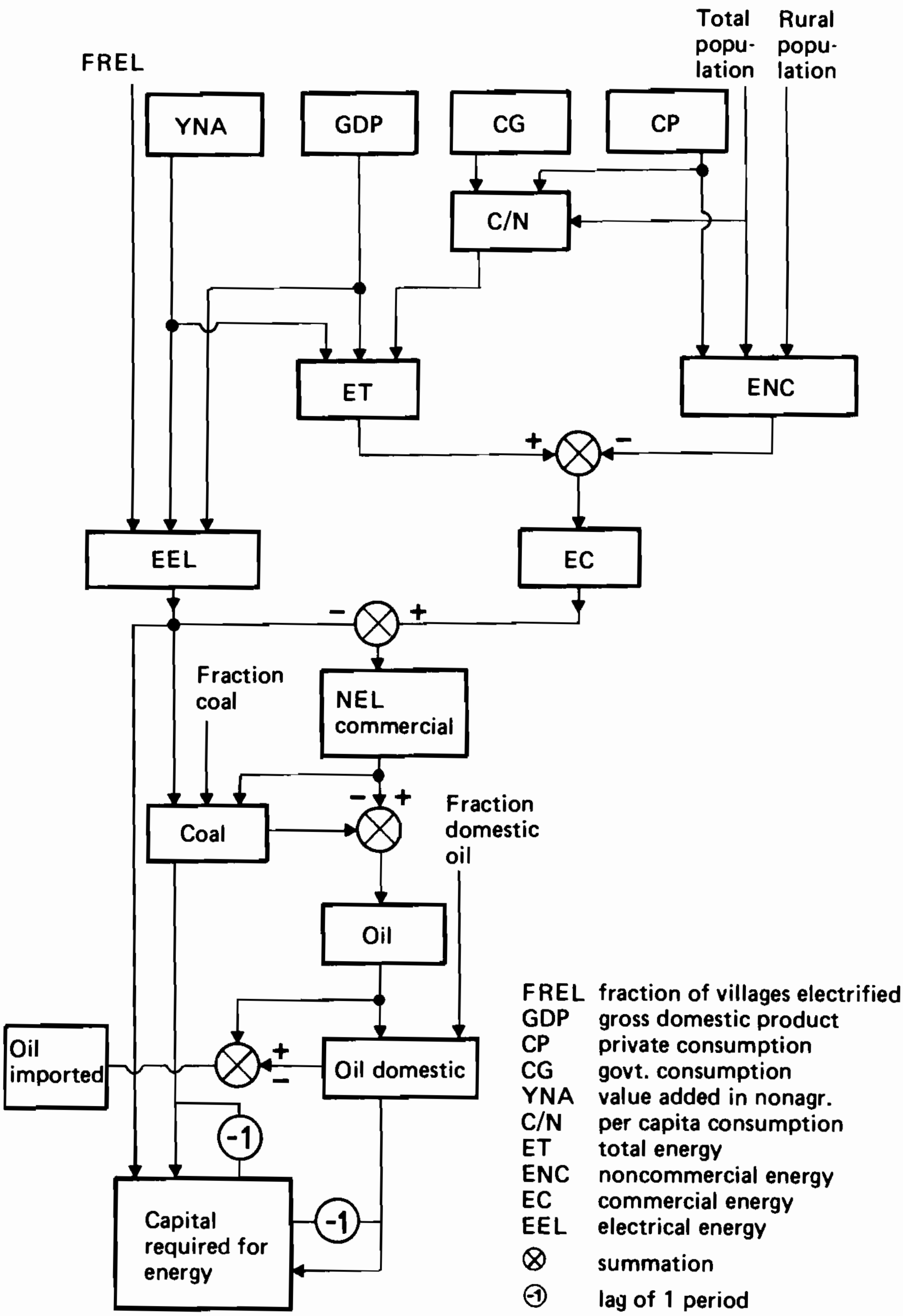


FIGURE 3 The model structure – the energy sector.

oil is specified to increase annually and to stabilize at a given level. Since the foreign exchange requirement for imported oil is subtracted from the total import availability in order to obtain imports of other raw materials, machinery, and the like, this requirement provides a feedback to the macroeconomic model, which permits investigation of the effects of oil prices on the development of the economy.

The capital required for the energy sector is then calculated using capital coefficients for the various forms of energy. Nonelectrical energy is assumed to come from coal and oil. We emphasize that this is done only to arrive at crude figures of investment requirements, ensuring the compatibility of the energy demand scenarios with the macroeconomic scenarios. The more detailed work on this aspect is being carried out within a linear programming framework using the MESSAGE model developed in the ENP at IIASA (Agnew, Schrattenholzer, Voss, 1978). In this work, a wide variety of energy conversion technologies and renewable resources are considered under various assumptions about the availability of fossil fuels. The demand results obtained from the SIMA model would be used as inputs into the MESSAGE model. If the energy supply strategy identified by the MESSAGE model is not consistent with the assumption of the particular run of the SIMA model, a new run of the SIMA model would be made with modified parameters, followed by another run of the MESSAGE model. If, in the total investment in the economy, the share of investment in the energy sector constitutes a much larger fraction of the GDP than it does at present, then it is necessary to introduce a feedback in the investment availability for the nonagricultural sector. Investment in energy above today's level can be subtracted from the investment available for nonagriculture; this will slow down the development of the economy and, in turn, the demand for energy. In the initial runs of the SIMA model, the capital stock (K) for energy is considered to be

$$\begin{aligned} K_{\text{electricity}} &= K_{\text{capacity generation}} + K_{\text{transmission}} \\ &\quad + K_{\text{rural electricity}} \\ K_{\text{coal}} &= K_{\text{exploration}} + K_{\text{mines}} + K_{\text{railways}} \\ K_{\text{oil}} &= K_{\text{exploration}} + K_{\text{wells}} + K_{\text{refining}} \end{aligned}$$

Prices in the Model

The model is estimated from data at constant prices of 1970. There is no monetary sector in the model; therefore all the prices implicitly remain constant at their 1970 values. However, it is possible to change the prices of imports and exports and, in particular, the price of imported oil. All these changes are exogenously specified.

The Exogenous Variables

The important exogenous variables for the SIMA model are the growth rates of agriculture and exports, the projections of total and urban population, and the level of foreign aid. In the energy sector, the growth rate of the extension of the electricity network to rural areas, the shares of coal in electrical energy and in nonelectrical commercial energy, and the extent of self-sufficiency in oil are all specified as exogenous variables.

Readers not interested in the details of the model may skip the following section, which deals with the equations in the model.

THE EQUATIONS IN THE MODEL

The estimation of relationships is generally based on multiple regression analysis of the time series from 1950 to 1973, with some exceptions where the time series were shorter. In most cases, the data are from publications of the Government of India. The regressions were carried out by using the convenient program package developed by Norman (1978). To take account of autocorrelation, whenever it was indicated by the Durbin–Watson statistic, a first-order scheme was used, and the autocorrelation parameter space was scanned to obtain the maximum-likelihood estimate. An explanation of the symbols and units used can be found in Appendix B. In presenting the equations of the model in the text we have dropped the subscript for the current period from all variables. A subscript of -1 refers to the period preceding the current period.

The Agricultural Sector

The importance of the agricultural sector, from which, at present, almost 45 percent of the GDP originates, cannot be underestimated. Up until the mid-1960s the value added in the agricultural sector increased largely with the increase in the area under cultivation and in the irrigated area. However, over the past decade, growth in agricultural output has been principally due to the increased yields of the high-yielding crop varieties, which have ushered in the "green revolution" in agriculture in many underdeveloped countries. Growth in agricultural output in the future is much more likely to occur as a result of such technological progress and input intensification, rather than because of an extension of the area under cultivation, for which there is limited scope in India. The growth rate of the value added in the agricultural sector is prescribed exogenously:

$$YA = (1 + g)YA_{-1} \, , \tag{1}$$

where YA is the value added in the agricultural sector and g is the exogenously prescribed growth rate of agriculture.

However, to increase yields it is also necessary to increase investment in agriculture. The incremental capital/output ratio in agriculture increases with an increase in agricultural output, and an asymptotic function is prescribed as

$$KORA = KOA - (KOA - KIA)\frac{YA_{73}}{YA} \, , \tag{2}$$

where $KORA$ is the incremental capital/output ratio in agriculture, KOA is the eventual asymptotic incremental capital/output ratio in agriculture, and KIA is the initial incremental capital/output ratio in agriculture.

The Nonagricultural Sector

With increasing industrialization, the nonagricultural sector, including the energy sector, is likely to dominate the economy in the future. The value added in the nonagricultural sector depends on the productive capacity created through investment.

PRODUCTIVE CAPACITY

The incremental capital/output ratio in the nonagricultural sector in India has been high and seems to have been increasing over the last few years. This is conceivable in the preliminary stages of a developing economy in which large resources are used for building up the infrastructure, the heavy engineering capability, and the social services. The incremental capital/output ratio could be expected to decline in the future. An asymptotic function is specified to reflect this for the *capacity output of the nonagricultural sector.*

$$KOR = KO + (KI - KO)\frac{\overline{KINA}_{73}}{KINA_{-1}} \, , \tag{3}$$

$$YNAC = YNAC_{73} + \frac{KINA_{-1} - \overline{KINA}_{72}}{KOR} , \qquad (4)$$

where KOR is the incremental capital/output ratio; KO and KI are the eventual (2030) and initial (1973) incremental capital/output ratios for the nonagricultural sector, respectively; $KINA$ is the capital stock in the nonagricultural sector; and $YNAC$ is the capacity output of the nonagricultural sector.

The incremental capital/output ratio decreases asymptotically from its initial value KI (4.5 in 1973–1974) to KO as the capital stock in nonagriculture, reflecting the diversification of the industrial base, increases (see Figure 2). In some simulation runs, KO is set to be the same as KI; therefore, the incremental capital/output ratio remains constant at the 1973 level.

Output in the nonagricultural sector will depend on the availability of imported raw materials and imported spare parts for maintenance. Thus, the *capacity utilization* may be written as

$$UC = \min\left(1.0, \frac{M245\text{–}9}{M2459D}\right) , \qquad (5)$$

where UC is the capacity utilization fraction, $M245\text{–}9$ is nonfuel imports of goods, and $M2459D$ is the imports required for full-capacity operations. Thus, the *value added in the nonagricultural sector YNA will be*

$$YNA = UC \cdot YNAC . \qquad (6)$$

TOTAL GDP

The *GDP at market prices YD* is given as

$$\begin{aligned} YD = \underset{(103.7)}{1.0952}(YA + YNA) - \underset{(1.41)}{4077.2} , \qquad (7) \end{aligned}$$

$$R^2 = 0.999, \quad DW = 1.73, \quad 1950\text{–}1973.$$

YD is not just the sum of YA and YNA because YA and YNA are in producers' prices. In this and the subsequent equations the numbers in parentheses below the coefficients are the t values, R is the correlation coefficient, DW is the Durbin–Watson statistic, and the period, e.g., 1950–1973, refers to the period covered by the time series on which the regression is based.

CONSUMPTION

Per capita *private consumption* CP is dependent on per capita income after tax and it increases when the share of agriculture increases:

$$\frac{CP}{N} = \underset{(34.2)}{0.7617}\left(\frac{YD - TX}{N}\right) + \underset{(4.14)}{48.74}\left(\frac{YA}{YNA}\right) + \underset{(1.14)}{13.59}\ , \qquad (8)$$

$$R^2 = 0.94,\ \ DW = 1.57,\ \ 1950\text{–}1973,$$

where N is population, and TX is taxes collected.

Public consumption is a function of the taxes collected by the government CG:

$$CG = \underset{(30.8)}{0.8022}TX_{-1} + \underset{(1.51)}{1355.2}\ , \qquad (9)$$

$$R^2 = 0.98,\ \ DW = 1.53,\ \ 1951\text{–}1973.$$

These *taxes* depend on the composition of the GDP:

$$TX = \underset{(3.41)}{0.1345}YA_{-1} + \underset{(5.08)}{0.1918}YNA_{-1} + \underset{(1.26)}{0.03}\ , \qquad (10)$$

$$R^2 = 0.99,\ \ DW = 1.75,\ \ 1951\text{–}1973.$$

INVESTMENT

Public sector investment IG depends on foreign aid and government income from taxation.

$$IG = \underset{(5.97)}{0.4086}TX + \underset{(1.99)}{0.7886}F + \underset{(0.85)}{2641.1}\ , \qquad (11)$$

$$R^2 = 0.78,\ \ DW = 1.85,\ \ 1957\text{–}1972,$$

where F is foreign aid in constant rupees of 1970.

The *desired gross fixed investment* IFD in the economy increases relative to the increase in the GDP and in government investment:

$$\log IFD = \underset{(10.5)}{0.7199}\log IG + \underset{(3.33)}{0.5792}\log(YD_{-1}) - \underset{(-2.31)}{3.7965}\ , \qquad (12)$$

$$R^2 = 0.97,\ \ DW = 1.30,\ \ 1951\text{–}1972.$$

However, the *actual gross fixed investment* IF in the economy is constrained by available savings, obtained from the GDP identity

$$IF = \min\{IFD, 0.95[YD - (CP + CG + X - M)]\}, \tag{13}$$

where X is exports of goods and services in constant rupees of 1970, and M is imports of goods and services in constant rupees of 1970, excluding net factor income payments abroad. Minimum inventory formation is assumed to form 5 percent of the actual gross fixed investment. *Actual inventory formation INV* is obtained by

$$INV = YD - (CP + CG + X - M) - IF. \tag{14}$$

The replacement requirement for depreciated capital stock IR should depend on the gross fixed investment made in the past. Although, in principle, the replacement requirements should be made endogenous with a 20-year to 30-year lag, for computational convenience, this is not done, and the replacement requirement is taken to be 10 percent of gross fixed investment. *Net fixed investment in the nonagricultural sector INA* is obtained by subtracting the net fixed investment required for agriculture and the replacement requirement from gross fixed investment:

$$IR = 0.1IF, \tag{15}$$

$$INA = IF - IR - KORA(YA - YA_{-1}), \tag{16}$$

$$KINA(t) = \sum_{\tau=1950}^{t-1} INA(\tau) + INA(t). \tag{17}$$

EXPORTS

Exports of goods depend on the volume of world trade, relative prices, and domestic production of manufactured goods. Since such a function would require an exogenous specification of the volume of world trade, we prescribe that total (goods and services) exports grow at an exogenously prescribed growth rate ϵ:

$$X = (1 + \epsilon)X_{-1}. \tag{18}$$

IMPORTS

Imports of raw materials and spare parts depend on nonagricultural output, and imports of machinery depend on the level of investment. However, as the economy develops, this dependence on imports diminishes. Thus, *demand for such imports, required for full-capacity operations*, is obtained by

$$\frac{M2459D}{YNA} = \underset{(0.34)}{0.0306} + \underset{(3.35)}{\frac{0.0397}{\log(KINA_{-1}/100)}} - \underset{(-1.95)}{\frac{0.0472}{\log IF}}, \tag{19}$$

$R^2 = 0.70,\ DW = 1.59.$

This makes $M2459D/YNA$ asymptotic to 0.0306 over the long term. The demand for imports can be met only if foreign exchange is available. *Imports are restricted by the availability of foreign exchange* as determined by exports, private transfers, and foreign aid.

$$M = (PX \cdot X + F + TFP - YF)/PMT, \tag{20}$$

$$M0\text{–}9 = 0.80M, \tag{21}$$

where TFP is private transfers from abroad in constant rupees, YF is net factor income payments abroad in constant rupees, PX is the index of export prices, with base 1970 = 1, PMT is the index of import prices, with base 1970 = 1, and $M0\text{–}9$ is imports of goods of Standard International Trade Classification (SITC) sectors 0 to 9. Net factor income payments abroad are a function of the foreign aid loans or private capital inflows received up to the present:

$$YF = 0.021 \cdot CTG_{-1}, \tag{22}$$

where CTG_{-1} is the cumulative trade gap for the period preceding the current period.

Assuming no imports of food (SITC sectors 0 and 1) and normal weather, more resources are available for imports of fuel (which, for India, is oil), raw materials, and manufactured goods corresponding to SITC sectors 2, 4, and 5 to 9. Imports of fuel are made first, and the remaining exchange is used to import raw materials and manufactured goods.

$$M3 = PM_{\text{oil}} \cdot OIL^M, \tag{23}$$

$$M245\text{–}9 = M0\text{–}9 - M3, \tag{24}$$

where $M3$ is oil imports in 1970 rupees, OIL^M is oil imports in millions of tons, and PM_{oil} is the import price of oil in constant rupees per ton.

As the price of imported oil is varied in different scenarios relative to the price of other imports, the index of import prices PMT has to be adjusted. It is obtained as the weighted price of imports of oil and nonoil.

$$PMT = PM\left(\frac{M - M3}{M}\right) + \frac{PM_{\text{oil}}}{PM_{\text{oil}_0}} \cdot \frac{M3}{M}, \tag{25}$$

where PM is the index of import prices of nonoil, with base 1970 = 1, and PM_{oil_0} is the base import price of oil in rupees of 1970, taken to be Rs 560 per ton.

Since the SIMA model is a long-term model, trade has to be balanced, although, in reality, fluctuations may continue. Thus the *trade gap* occurs only because of foreign aid. The cumulative trade gap CTG depends on the fraction of aid that is assumed to be from foreign loans FL:

$$CTG = CTG_{-1} + FL \cdot F . \tag{26}$$

Gross available products Y may be written as

$$Y = YD + M - X . \tag{27}$$

The Energy Sector

Having created a macroeconomic framework, the next step is to obtain reasonably reliable figures for the likely energy demand by relating energy consumption to the structure of the GDP. Some clarifications of the energy consumption data used in India are set out in Appendix C.

ENERGY DEMAND

The per capita energy demand ET increases with an increase in the share YNA/YD of the nonagricultural sector in the GDP and with an increase in per capita consumption C/N:

$$\log(ET/N) = \underset{(6.1)}{0.344} \log(YNA/YD) + \underset{(4.6)}{0.338} \log(C/N) - \underset{(-5.3)}{2.623} ,$$
$$R^2 = 0.93, \quad DW = 0.94, \quad 1953\text{–}1971. \tag{28}$$

The share of *noncommercial energy demand* ENC in total energy declines with increasing urbanization, as measured by the fraction of the population that is urban NU/N, and with private per capita consumption CP/N:

$$\log(ENC/ET) = 2.6529 - \underset{(-4.0)}{0.5239} \log(NU/N) - \underset{(-4.78)}{0.6212} \log(CP/N) ,$$
$$R^2 = 0.97, \quad DW = 1.68, \quad 1953\text{–}1971. \tag{29}$$

The share of *commercial energy demand* EC can then be obtained as a residual:

$$EC = ET - ENC\,. \tag{30}$$

The growth rate of electrical energy supply in the developing countries is usually higher than in the developed world because there is usually a large backlog of demand for electricity in rural areas. In 1972, one-quarter of all villages in India were receiving electricity. The pace at which full electrification will be reached is represented in the SIMA model as a scenario variable. The share of electrical energy in the commercial energy sector rises with the number of villages supplied with electricity as a percentage of the total number of villages *FREL* and with the activities in the nonagricultural sector. *Electrical energy demand EEL* may be written as

$$\begin{aligned} \log(EEL/EC) &= \underset{(-12.2)}{-3.78} + \underset{(10.4)}{0.2985}\log(FREL) + \underset{(1.91)}{0.2378}\log(YNA/YD)\,, \\ R^2 &= 0.98,\quad DW = 1.81,\quad 1953\text{–}1971. \end{aligned} \tag{31}$$

Nonelectrical energy demand NEL, therefore, is

$$NEL = EC - EEL\,. \tag{32}$$

CAPITAL REQUIRED FOR THE ENERGY SECTOR

India has abundant coal, small gas reserves, and moderate oil resources. For the present, we do not include the recurring maintenance and operating cost requirements for the energy sector, but consider only the capital requirements for additional facilities.

Taking the different load factors into consideration, we assume that, in the long run, the capital costs per kilowatt (kW) of capacity will be approximately Rs 3,000 for coal, hydroelectric power (which, in the future, would have a very low load factor), or nuclear power (with a higher load factor than coal), even though hydroelectric power and coal are cheaper at present. These costs include transmission and distribution costs. However, for supplying rural areas with electricity, special efforts to set up subtransmission lines have to be made; they require additional investment. Thus total *capital for electricity production* is obtained as

$$DFREL = FREL - FREL_{-1}\,, \tag{33}$$

$$DEKW = (EEL - EEL_{-1})1.42\,, \tag{34}$$

$$KEL = 3{,}000DEKW + 82{,}500DFREL\,, \tag{35}$$

where *DFREL* is the additional number of villages supplied with electricity as a percentage of the total number of villages; *DEKW* is the additional electrical capacity required, in millions of kilowatts, assuming a utilization factor of 4,000 kWh/kW; and *KEL* is the capital investment required for electricity, in millions of constant rupees.

The amount of coal required, in millions of tons, is

$$COAL = NEL \cdot F_{coal} , \tag{36}$$

where F_{coal} is the fraction of nonelectrical energy coming from coal. Thus the additional annual coal requirement, that is, coal used for more than nonelectrical energy production, would be

$$DCOAL = COAL - COAL_{-1} + \frac{1}{1.42} DEKW\, F_{el}^{cl} , \tag{37}$$

where *DCOAL* is the additional annual coal requirement, in millions of tons, and F_{el}^{cl} is the fraction of electricity generated from coal-based plants.

At present the capital requirement for mining and transporting one ton of additional coal is Rs 210. However, as mines become deeper and railroads get congested, the capital requirements will continue to increase. The *annual capital needed to increase coal capacity by the additional annual coal requirement* is

$$KCOAL = K_{coal}^{mine} + K_{coal}^{transp.} , \tag{38}$$

$$KCOAL = 210(1 + \rho_{coal})^t DCOAL , \tag{39}$$

where ρ_{coal} is the exogenously specified growth rate of the capital cost of mining and transporting coal.

Since the amount of electricity generated by oil-based plants is negligible at present, oil requirements are assumed to be for nonelectrical uses only. The amount of oil required *OIL*, in millions of tons, is

$$OIL = 2(NEL - COAL) . \tag{40}$$

Of this, OIL^D will be domestic oil. The availability of domestic oil is exogenously assumed to stabilize at various levels for different scenarios. The capital required K_{oil}^D for exploration and drilling to increase domestic oil production, is

$$K_{oil}^D = 3{,}000(OIL^D - OIL_{-1}^D) . \tag{41}$$

This could also be obtained through coal liquefaction, in which case the capital requirements per ton of production capacity are assumed to be the same – Rs 3,000 per ton. The additional annual oil requirement *DOIL*, in millions of tons, is

$$DOIL = (OIL - OIL_{-1}) . \tag{42}$$

Even though some crude oil is imported, it is assumed that all oil will continue to be refined in India. The capital required to increase the refinery capacity $K^{\mathrm{R}}_{\mathrm{oil}}$ is

$$K^{\mathrm{R}}_{\mathrm{oil}} = 120 \cdot DOIL . \tag{43}$$

Thus, total *capital required for oil production KOIL* is

$$KOIL = K^{\mathrm{D}}_{\mathrm{oil}} + K^{\mathrm{R}}_{\mathrm{oil}} . \tag{44}$$

Thus one may add up the various capital requirements to obtain the *total annual capital for the energy sector KEN*, in millions of rupees:

$$KEN = KEL + KCOAL + KOIL . \tag{45}$$

This capital requirement is only for net investment. Investment for the replacement of depreciated capital stock in the energy sector is included in the aggregate replacement requirements. With the exception of coal, for which a 1.5 percent increase in capital cost per year is assumed, the capital costs of other energy supplies are kept constant. The oil industry has been developed relatively recently in India, and future increases in costs because of resource depletion should be compensated for by the benefits of experience. The electrical power plant industry is well established, and one may not expect any change in costs. If the future energy supply is to be based on a much more expensive energy source, the demand projection would need to be revised.

In addition to the capital costs in the energy sector, one should also consider operating and import costs in order to account for the total cost of energy. Costs of oil imports can be determined from the import price of oil, which is exogenously given. A gradual increase in the price of imported oil is assumed. If oil prices were to rise suddenly, then the energy demand estimated might need to be revised. The nonfuel operating costs of coal mines, power plants, oil refineries, and transport and transmission networks have to be added to operating and import costs.

3 GENERATION OF SCENARIOS AND NUMERICAL RESULTS

THE SCENARIO SPECIFICATION

Different scenarios can be generated by specifying alternative sets of values for the exogenous variables and by altering some of the relationships involving certain endogenous variables. For example, the tax equation can be modified to reflect increased government effort at development. Similarly, the incremental capital/output ratio can be changed to reflect increased capital costs of energy, if such a supply scenario is envisaged.

Although a large number of scenarios could be generated with the model, we restrict ourselves to a few that are of policy interest, evaluating these against a "base case." The simulation carried out covers the period from 1974 to 2030, and the results of these runs are presented in this section. The base case will be described in detail, whereas only the important results of the other scenarios are given. The scenarios are constructed so that each one represents an additional policy measure, and, therefore, the growth of the economy improves with each additional step, the base case being the lowest of all.

THE BASE CASE

The Scenario Specification of the Base Case

The base case is considered to be a "business as usual" scenario in which no drastic policy changes or shifts in the availability of resources take place. The exogenous parameters and their specifications for the base case, and for the other scenarios, together with some initial conditions, are given in Tables 1 and 2. Some observations on these specifications follow.

To specify total population as well as its urban/rural makeup, the medium variant projections of the United Nations (1975) for population and urbanization are taken as reference points for the year 2000. An asymptotic equation is obtained by assuming that eventually the population stabilizes at $1{,}500 \times 10^6$.

$$N = 1{,}500/(1 + 1.5e^{-0.375t}), \quad t = 1 \text{ in } 1974 . \tag{46}$$

This gives a population estimate for the years 2000 and 2030 of 958×10^6 and $1{,}267 \times 10^6$, respectively. The growth rate of urbanization estimated from the medium variant figure given by the United Nations (1975) for 2000 is 1.627 percent. This gives an estimate of urban population as 32 per-

TABLE 1 Exogenous parameters and variables and their specifications.

Symbol	Exogenous parameters and variables	Value
N	Population ($\times 10^6$)[a]	
NU	Urban population ($\times 10^6$)[a]	
IR	Investment for replacement of depreciated capital stock (Rs $\times 10^6$)[a]	
KI	Initial incremental capital/output ratio for the nonagricultural sector	4.5
KO	Long-term incremental capital/output ratio for the nonagricultural sector[b]	
KOA	Long-term incremental capital/output ratio for the agricultural sector[b]	
KIA	Initial incremental capital/output ratio in agriculture	2.5
ρ_{coal}	Growth rate of capital costs of coal (%)	1.5
ρ_{oil}	Growth rate of import price of oil (%)	2.0
ER	Exchange rate (Rs/$ of 1970)	7.5
PX	Index of exports prices (base 1970 = 1)	1.4
PM	Index of nonoil imports prices (base 1970 = 1)	1.5
F	Foreign aid (constant Rs $\times 10^6$ of 1970)[a]	
FL	Fraction of foreign aid given as loans	0.5
TFP	Private transfers from abroad (constant Rs $\times 10^6$)[a]	
$FREL$	Number of villages supplied with electricity as a percentage of total number of villages[a]	
F_{coal}	Fraction of nonelectrical energy from coal[a]	
OIL^D	Domestic oil production (10^6 tons)[b]	
F_{el}^{cl}	Fraction of electricity generated from coal-based plants	0.5

[a]Values depend on time but do not change with scenarios and are given in Table 4.
[b]Exogenous variables that change for each scenario; values given in Table 3.

TABLE 2 Exogenous variables for different scenarios.

Scenarios	Percentage annual growth rate: Base case 1	Lower KOR^a 2	Increasing aid 3	High growth due to high tax[b] 4
Export	5.0	5.0	5.0	7.0
Agr. output	3.0	3.0	4.0	4.0
Foreign aid	0	0	3.0	3.0
Asymptotic KOR^a for nonagr.	4.5	2.5	2.5	2.5
Stabilization level of domestic oil production (10^6 tons)[c]	45.0	45.0	65.0	90.0

[a] *KOR* is incremental capital/output ratio.
[b] The tax rate (*Tx*) is increased by 50 percent without affecting public government consumption (*CG*) by tax and public consumption equations

$$Tx = 1.5(0.2117YA_{-1} + 0.2395YNA_{-1} - 277.4)$$
$$CG = 0.8033(0.667)Tx_{-1} + 1308 .$$

[c] The actual growth over time is given for each scenario in summary tables.

cent and 52 percent of total population by 2000 and 2030, respectively, assuming the same growth rate after 2000.

An asymptotic equation for the supply of electrification to rural areas is obtained by assuming that, starting from a base level of 25 percent in 1972, by 2000 90 percent of rural areas receive electricity, and by 2025 all rural areas have electricity.

$$FREL = 100/(1 + 2.81e^{-0.124t}) , \quad t = 1 \text{ in } 1974 . \qquad (47)$$

It was assumed in all scenarios that two-thirds of nonelectrical energy is obtained from coal by 1980 and that the capital cost for coal increases by 1.5 percent annually.

The import price of oil also increases by 2.0 percent annually. This means that the price of oil in rupees of 1970 is Rs 560 per ton in 1974, increasing to Rs 1,200 by 2016, and stabilizing thereafter. The definition of the base case and variations over the base case are illustrated in Figure 4.

The Numerical Results of the Base Case

Numerical results for every 5 years are given in Table 3, and several important variables are plotted in Figures 5 and 6. The per capita GDP increases

DEFINITION OF THE BASE CASE

"DRIFT" SCENARIO DETERMINED BY PAST INPUTS

- Growth in agricultural output 3% (1950–1973 growth rate = 2.3%)
- Foreign aid constant at $1,000 × 10^6/year (current rate)
- Marginal capital/output ratio in nonagriculture remains constant at a value of 4.5

INPUTS COMMON TO ALL SCENARIOS

	1971	2000	2025
• Total population (× 10^6)	570	960	1,230
• Urban population (% of total)	20	32	48
• Villages electr. (% of total)	25	90	99

	% Growth rates
• Exports	5.0
• Price of oil	2.0
• Capital cost for coal	1.5

VARIATIONS OVER BASE CASE

A "Low incremental capital/output ratio"

- Incremental capital/output ratio in nonagriculture decreases to a value of 2.5
- Otherwise like base case

B "High agr. growth, increased foreign aid"

- Agricultural growth rate increases to 4% (from 3%)
- Foreign aid growth rate increases to 3%
- Otherwise like A

C "High growth"

- Tax rate increases by 50%
- Export growth rate increases to 7% (from 5%)
- Otherwise like B

FIGURE 4 Definition of the base case of the SIMA model and scenario generation (through exogenous specifications).

from Rs 687 in 1970, to Rs 1,478 in 2000, and to Rs 3,628 in 2030. The GDP growth rate of 2.5 percent is modest but is an improvement on the growth rate of less than 1.5 percent over the past three decades. The overall GDP growth rate is 4.3 percent. This is slightly better than the economy's past performance in the base case, which has been described above as business as usual, without major policy changes, and is not unreasonable. Until recently, the population growth rate had been decelerating at a faster rate than expected. Moreover, the performance of the export sector has also improved significantly in the recent past. Per capita annual consumption of total (commercial and noncommercial) energy increases from 0.49 tons of coal equivalent (tce) in 1970, to 0.68 tce in 2000, and to 0.94 tce in 2030. The per capita consumption of commercial energy, however, increases at a faster rate than the per capita consumption of total energy, increasing from 0.165 tce per capita in 1970, to 0.43 tce in 2000, and 0.79 tce in 2030. Since commercial energy is usually used more efficiently than noncommercial energy, the total usefully consumed energy increases at a faster rate than that shown by the primary energy consumption in coal equivalent units. Moreover, the commercial energy consumption considered here excludes conversion losses and therefore appears smaller than the actual energy production required, as can be seen by adding together the net primary energy of coal, oil, and electrical energy produced from coal.

Electrical energy demand grows from 67×10^9 kilowatt hours in 1975 to 376×10^9 kWh in 2000 (including distribution losses), that is, an annual growth rate of 7 percent. However, its long-term growth rate is small (4.9 percent), because of the low growth rate of the GDP. The capacity requirements are 92 gigawatts (GWe) in 2000 and 230 GWe in 2030.

The capital requirements in the energy sector are especially high in the initial years because of oil exploration activities and the extension of the electricity supply to rural areas, requiring 10–18 percent of government investment; in later years, import requirements rise. During the period 1980–1990, the imported oil requirements decline because of increases in domestic oil production, and only 8–11 percent of export earnings is required for importing oil. Domestic oil production stabilizes at 45×10^6 tons per year in 2005. In 2030, 42 percent of total export earnings is required to import almost 100×10^6 tons.

The coal requirements, including the requirements for power generation, are 345×10^6 tons in 2000, increasing to 845×10^6 tons in 2030.

ALTERNATIVE SCENARIOS

In addition to the base case, three alternative scenarios were run. The parameters, which were varied in these scenarios, are summarized in Table 2,

TABLE 3 The base case results.[a]

	1975	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030	1.RATE	2.RATE
YA/YD	0.42	0.38	0.35	0.33	0.31	0.28	0.26	0.25	0.26	0.24	0.23	0.21	-1.55	-1.23
YD	457.68	587.82	725.50	900.31	1127.32	1416.10	1776.71	2133.58	2438.00	2957.93	3656.98	4595.51	4.62	4.28
YA	192.83	221.22	256.45	297.30	344.65	399.55	463.18	536.96	622.48	721.63	836.56	969.81	3.00	3.00
YNA	231.15	319.22	409.19	527.55	606.47	897.27	1162.97	1414.50	1607.91	1980.94	2506.01	3230.38	5.57	4.91
C	381.25	479.39	585.16	718.78	890.21	1109.67	1383.84	1657.47	1890.42	2288.50	2620.16	3538.75	4.37	4.13
CP	327.94	408.25	497.03	609.01	752.88	935.94	1164.51	1389.19	1583.20	1920.53	2362.75	2960.05	4.28	4.08
CG	53.43	71.14	87.94	109.41	137.43	173.84	219.46	268.05	307.47	367.50	456.36	575.45	4.83	4.42
TX	64.91	86.94	107.93	134.70	169.63	215.02	271.88	332.45	381.60	456.42	567.19	715.66	4.91	4.46
IG	33.39	42.41	50.97	61.90	76.18	94.72	117.96	142.71	162.79	193.36	238.62	299.28	4.26	4.07
I	83.29	116.45	147.91	187.79	239.89	305.17	377.50	438.75	478.81	580.34	720.93	914.08	5.33	4.45
IF	74.03	103.17	132.97	173.20	227.87	289.90	358.59	417.15	454.48	552.07	685.16	871.09	5.61	4.56
IAG	14.65	18.75	23.51	29.02	35.41	42.82	51.41	61.37	72.92	86.30	101.82	119.81	4.39	3.90
INA	51.98	74.10	96.17	126.86	169.62	218.04	271.30	314.22	335.99	410.43	516.53	667.28	5.90	4.75
INV	9.14	13.28	15.12	14.92	12.04	15.29	18.90	21.67	24.19	28.85	34.64	42.05	2.08	2.81
IR	7.40	10.32	13.30	17.32	22.78	28.99	35.86	41.73	45.44	55.21	68.61	87.30	5.61	4.59
X	19.71	25.15	32.10	40.97	52.29	66.73	85.17	108.70	138.73	177.06	225.98	288.41	5.00	5.00
PX	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	00.00	00.00
PM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	00.00	00.00
F	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	00.00	00.00
TFP	2.00	3.60	3.97	4.39	4.85	5.00	5.00	5.00	5.00	5.00	5.00	5.00	3.73	1.68
YF	0.06	0.34	0.62	0.90	1.18	1.46	1.74	2.02	2.31	2.59	2.87	3.15	13.92	7.59
H	26.87	33.17	39.22	46.43	55.15	65.57	69.95	70.92	70.51	86.60	110.05	142.97	3.63	3.09
PMOIL	571.20	630.65	696.29	768.76	848.77	937.11	1034.65	1142.34	1260.00	1260.00	1260.00	1260.00	2.00	1.45
MOIL	7.07	4.74	6.53	9.09	11.96	14.96	28.15	44.39	60.97	78.56	98.93	122.21	3.04	5.32
M245-9	14.63	19.07	20.68	23.35	27.22	31.42	35.82	35.02	29.26	34.37	44.26	60.08	3.11	2.60
YDPC	705.47	861.26	964.52	1095.24	1264.35	1478.08	1739.88	1975.86	2148.84	2500.14	2978.10	3628.58	2.78	2.92
CPPC	534.30	598.16	660.64	740.67	844.35	976.87	1140.36	1286.48	1395.50	1622.94	1925.02	2338.40	2.44	2.72
CGPC	87.08	104.23	116.84	132.99	154.15	181.47	214.93	248.19	271.06	310.48	371.65	454.10	2.98	3.05
ETPC	0.50	0.54	0.57	0.60	0.63	0.67	0.72	0.75	0.77	0.82	0.87	0.94	1.16	1.14
ECPC	0.18	0.23	0.27	0.32	0.37	0.43	0.50	0.54	0.58	0.64	0.71	0.79	3.55	2.71
ENCPC	0.32	0.31	0.29	0.27	0.26	0.24	0.22	0.21	0.19	0.18	0.17	0.15	-1.18	-1.37
EELPC	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.09	0.10	0.12	0.13	5.20	3.56
ET	309.42	367.97	425.58	490.38	563.65	644.95	733.06	812.30	875.56	966.02	1070.69	1190.61	2.98	2.48
EC	111.20	157.32	206.07	264.58	334.19	415.05	505.52	588.10	655.25	754.00	868.12	999.42	5.41	4.07
ENC	198.10	210.64	219.61	225.96	229.43	229.86	227.50	224.24	220.26	212.14	202.70	191.50	0.60	-0.06
EEL	11.67	18.95	27.47	37.96	50.38	64.70	80.56	94.78	105.92	122.67	142.20	164.81	7.09	4.93
MEL	99.40	138.37	178.66	226.72	283.77	350.30	424.92	493.34	549.31	631.38	726.11	834.91	5.16	3.94
OIL	20.39	23.52	30.38	38.55	48.23	59.54	72.23	83.87	93.38	107.34	123.47	141.97	4.38	3.59
OILD	8.00	16.00	21.00	26.70	34.13	43.56	45.00	45.00	45.00	45.00	45.00	45.00	7.01	3.19
OILM	12.38	7.52	9.38	11.82	14.09	15.98	27.22	38.87	48.39	62.34	78.50	96.99	1.02	3.81
KOR	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	00.00	00.00
KORA	2.56	2.83	3.06	3.25	3.42	3.57	3.70	3.81	3.90	3.99	4.06	4.12	1.34	0.87
N	613.55	682.51	752.64	822.72	891.55	957.98	1021.06	1080.02	1134.32	1183.66	1227.93	1267.23	1.80	1.33
NU	132.39	159.65	190.85	226.15	265.66	309.45	357.55	409.97	466.77	528.01	593.79	664.30	3.45	2.98
NR	481.16	522.86	561.79	596.57	625.88	648.53	663.52	670.05	667.55	655.65	634.14	602.93	1.20	0.41
FREL	287.17	428.20	581.96	721.28	827.90	899.42	943.26	968.65	982.89	990.72	994.99	997.30	4.67	2.29

[a] See Appendix B for an explanation of the symbols.

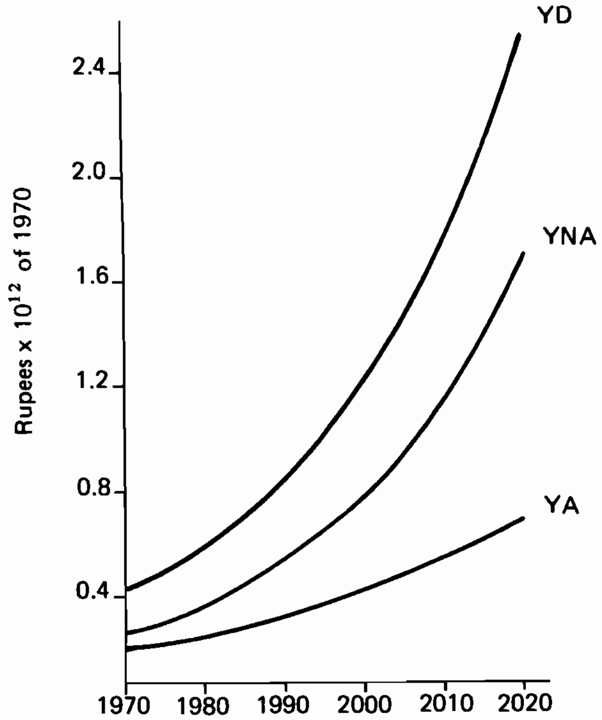


FIGURE 5 The GDP and sectoral outputs for the base case in rupees x 10^{12} of 1970.

and the important details of the results for these scenarios for selected years are given in Appendix D. To emphasize the effects of the changes in assumptions, the important results are summarized for the years 2000 and 2030 in Table 4.

In discussing the results, we refer mostly to the values for 2000, because in 2030 the same phenomena are only extended further in time; this can be seen in the comparative table provided in Appendix D.

The "Lower Incremental Capital/Output Ratio" Scenario

The incremental capital/output ratio in nonagriculture, which has been increasing over the past two decades and has been assumed to remain at a value of 4.5 (its recent value) in the base case, is assumed to decrease asymptotically to 2.5 (see Figure 2). Thus, this scenario will indicate the effects of a more efficient use of capital, which can be expected through diversification of capital stock, through the formation of a skilled labor force, or through the introduction of appropriate policies. The annual

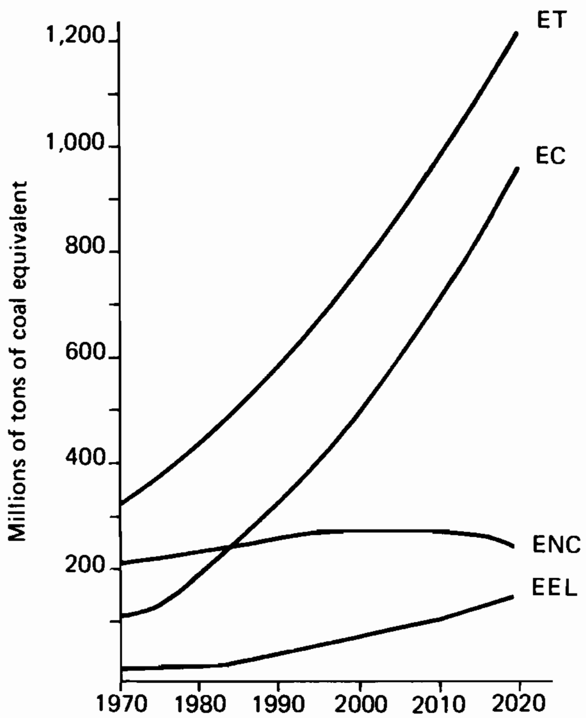


FIGURE 6 Consumption of energy for the base case in millions of tons of coal equivalent.

growth rate of the GDP is 5.46 percent between 1975 and 2000 and 4.55 percent between 1975 and 2030. The output of the nonagricultural sector grows at 6.74 percent and 5.25 percent for the same periods, respectively.

In this lower incremental capital/output scenario, energy requirements increase from 89 x 10^6 tce in 1970 to 482 x 10^6 tce in 2000 for commercial energy, from 174 x 10^6 tce to 224 x 10^6 tce for noncommercial energy, and from 263 x 10^6 tce to 706 x 10^6 tce for total energy. In 2030, the requirements are 1,075 x 10^6 tce for commercial, 187 x 10^6 tce for noncommercial, and 1,262 x 10^6 tce for total energy. Electrical energy generation increases from 55 x 10^9 kWh in 1970, to 446 x 10^9 kWh in 2000, and to 1,040 x 10^9 kWh in 2030. Electrical energy as a percentage of commercial energy is 8.99 percent for 1970, 15.89 percent for 2000, and 16.64 percent for 2030.

The net fixed investment requirements for producing, transforming, transporting, and transmitting fuels and energy account for 9.4 percent of the total net fixed investment in the economy in 2000 and 4.1 percent

TABLE 4 Summary results of different scenarios.

Variable symbols[a]	1970	2000 Base case 1	2000 1 + low KOR^a 2	2000 2 + high agr. + aid 3	2000 3 + high growth 4	2030 Base case 1	2030 1 + low KOR^a 2	2030 2 + incr. agr. + aid 3	2030 3 + high growth 4
YD (Rs x 10^9)[b]	398	1,416	1,727	1,809	2,620	4,595	5,277	6,932	22,442
YA/YD	0.48	0.28	0.23	0.29	0.20	0.21	0.18	0.24	0.07
YDPC (Rs)[b]	687	1,478	1,804	1,887	2,732	3,628	4,168	5,469	17,712
ET (10^6 tce)[c]	263	645	706	697	801	1,190	1,262	1,344	2,097
ENC (10^6 tce)[c]	174	229	224	214	209	191	187	168	135
EC (10^6 tce)[c]	89	415	482	483	592	999	1,076	1,176	1,962
EEL (10^9 kWh)[c]	55	378	448	436	553	960	1,041	1,117	1,960
ETPC (tce)[c]	0.49	0.67	0.74	0.73	0.84	0.94	1.00	1.06	1.65
ECPC (tce)[c]	0.16	0.43	0.50	0.50	0.62	0.79	0.85	0.93	1.55

[a] The variable symbols are as follows: *KOR* – incremental capital/output ratio; *YD* – GDP at market prices; *YA* – value added in the agricultural sector; *YDPC* – per capita GDP at market prices; *ET* – energy demand; *ENC* – noncommercial energy; *EC* – useful energy, excluding conversion losses, energy required in the energy sector, and transmission losses (to convert into primary energy, useful energy should be multiplied by a factor of one-quarter); *EEL* – electrical energy at a consumer point; *ETPC* – per capita energy demand; *ECPC* – per capita useful energy.

[b] \$1 is the equivalent of Rs 7.5.

[c] Coal in India has 5,000 kcal/kg, 1 x 10^6 tce of Indian coal is equal to 0.7125 x 10^6 tce of UN coal.

in 2030. However, these requirements account for approximately 30 percent of net government investment in 2000 and 12 percent in 2030. The three reasons for this decline are as follows: in 2030, investment in rural electrification is no longer required; oil imports increase (to generate export earnings for the purchase of oil, investment in other sectors, not considered here, would be required); and exports also increase.

The per capita GDP in 2000 rises from Rs 680 in 1970 to Rs 1,615, compared with Rs 1,339 in the base case. Total per capita energy consumption increases to 0.755 tce in 2000, compared with the base-case consumption of 0.08 tce.

The "Low Incremental Capital/Output Ratio, High Agricultural Growth, Increasing Foreign Aid" Scenario

Foreign aid increases at 3 percent annually in this case as compared to other cases, where it is kept constant at the level of Rs 5.5 billion a year, reaching a level of Rs 28 billion in 2030. From 1975 to 2030, the GDP and energy consumption grow at 5 percent and 4.36 percent, respectively.

The per capita GDP and per capita energy consumption rise to Rs 1,887 and to 0.50 tce, respectively, in 2000. Although this means that the capital requirements for energy increase, the economy is able to provide for these with the same percentage of fixed investment, since the level of fixed investment is also higher than in the base case. It should be noted that the high economic growth achieved through more rapid agricultural development and increasing foreign aid does not require a similar rise in the growth rate of energy consumption.

The "High Economic Growth" Scenario

The tax rate is increased by 50 percent, but the level of government consumption is not allowed to increase as a result of this, so the additional tax is available for public investment. The growth rate of exports is also increased to 7 percent, compared with 5 percent in the other scenarios. These changes are in addition to high agricultural growth, a low incremental capital/output ratio, and increasing foreign aid. This scenario projects a high economic growth rate and shows its effect on energy consumption. Although all the optimistic assumptions of this scenario may be considered unlikely to come about, the scenario is useful for defining some extreme values.

The high economic growth rate leads to 5.90 percent growth in the per capita GDP (Rs 2,732 by 2000, and Rs 17,712 by 2030) and 2.22

percent growth in the total per capita energy consumption reaching a level in 2030 of 1.65 tce per capita, of which commercial energy accounts for 1.55 tce. Although in the initial stage the increased tax rate restricts private consumption, the economy develops rapidly as these taxes are diverted to fixed investment; in less than 5 years this increases private consumption, as compared with private consumption in the base case.

4 CONCLUSIONS

During the period 1953–1971, when the price of energy was not high and India was at a preliminary stage of industrial development, the growth rate of commercial energy consumption was 5.3 percent, compared with the economic growth rate of 3.8 percent. In the base case, over the period 1975–2000, in which the commercial energy consumption growth rate is 5.4 percent, the economic growth rate is 4.6 percent. In the base case, for the period 1975–2030, the growth rate of commercial energy consumption is 4.0 percent, and the growth rate of the economy is 4.3 percent. However, over the short term, for example, 1975–1985, the growth rate of commercial energy consumption is higher at 6.3 percent, whereas the economic growth rate is 4.7 percent. In the high growth scenario, in which the economic growth rate is 7 percent, the growth rate of commercial energy consumption is relatively low (5.6 percent). Thus, the growth rate of commercial energy consumption increases with the growth rate of the economy, but at a slower rate. Moreover, the growth rate of commercial energy consumption falls with time, since the substitution of commercial energy for noncommercial energy is higher in the early years.

The energy demand generated from the scenarios with modest economic growth does not appear to pose any special problems of capital requirements for the energy sector. However, our estimates of the net capital requirement for the energy sector are fairly crude. A detailed supply analysis that uses these demand projections is under way. By optimizing the net capital investment for energy, the capital for replacement, and operating and maintenance costs, the analysis arrives at an optimal energy supply mix. It considers a wide variety of new energy conversion technologies, in order to obtain further insight into the capital requirements of the energy sector (J. Parikh and M. Agnew, Energy Supply Choices for India, in preparation).

From the numerical results of the four scenarios examined we can draw some conclusions:

(a) In 2000 (2030) the total energy consumption in India ranges from 645 x 10^6 tce (1,190 x 10^6 tce) to 801 x 10^6 tce (2,097 x 10^6 tce). Consumption of commercial energy, however, ranges from 415 x 10^6 tce (999 x 10^6 tce) to 592 x 10^6 tce (1,962 x 10^6 tce), growing at 5.4 percent and 7.3 percent until 2000 for the base case and high growth scenarios, respectively. Noncommercial energy consumption grows at 0.8 percent and 0.5 percent for the base case and high growth scenario, respectively, and has a zero or negative growth rate during the period 2000–2030 for all cases with the exception of the base case. As mentioned before, the high growth scenario is developed only to obtain upper limits and seems at present to be highly optimistic, even though it is feasible.

(b) The consumption of electrical energy in 2000 (2030) is projected to be between 378 x 10^9 kWh (960 x 10^9 kWh) and 553 x 10^9 kWh (1,960 x 10^9 kWh). Electrical energy is 15–17 percent of commercial energy consumption in 2030.

(c) The demand for noncommercial energy ranges between 135 x 10^6 tce and 191 x 10^6 tce, but as a percentage of total energy consumption, it declines to 15 percent or less in 2030. Such a level of noncommercial energy consumption for a period as long as 50 years may be considered ecologically undesirable. However, whatever substitutes are provided for noncommercial fuels, they must be institutionally acceptable and economically feasible.

(d) Comparisons between scenarios (b) and (c) show that macroeconomic growth, if achieved by an intensification of the nonagricultural sector, implies a substantial growth in the energy requirements. Economic growth achieved by an intensification of the agricultural sector does not have such a high energy requirement. However, this alone cannot be taken as a decisive factor in the consideration of alternative policies for macroeconomic growth. Foreign aid, at the level we have assumed (3 percent growth), has little impact on energy demand and the whole economy.

In addition to providing energy demand estimates up to the year 2030, the SIMA model provides insights into the growth rate of energy demand and its relation to macroeconomic variables.

Appendix A

COAL REPLACEMENT AND EQUIVALENT UNITS OF DIFFERENT FUELS

Fuel	Unit	Coal equivalent in tons (tce)	Coal replacement in tons (tcr)
Coal (coking 6,640 kcal/kg; noncoking coal used in steam generation 5,000 kcal/kg)	1 ton	1.0	1.0
Hard coke	1 ton	1.3	1.3
Soft coke	1 ton	1.5	1.5
Firewood and agricultural waste (4,750 kcal/kg)	1 ton	0.95	0.95
Charcoal (6,900 kcal/kg)	1 ton	1.0	1.0
Animal dung (3,300 kcal/kg dry)	1 ton	0.66	0.4
Oil products (10,000 kcal/kg)			
Kerosene and liquefied petroleum gas	1 ton	2.0	8.3
Diesel oil	1 ton	2.0	9.0
Motor spirit and jet fuel	1 ton	2.0	7.5
Natural gas (9,000 kcal/kg)	$10^3 m^2$	1.8	3.6
Electricity	10^3 kWh	0.172 electric or 0.6 thermal	1.0

Appendix B

THE SYMBOLS AND UNITS OF MEASUREMENT USED IN TABLE 3 AND TABLES D.1 TO D.3[a]

Symbol	Variable	Unit
YD	Gross domestic product (GDP)	Rs x 10^9 of 1970
YA	GDP from agricultural sector	Rs x 10^9 of 1970
YNA	GDP from nonagricultural sector	Rs x 10^9 of 1970
YNAC	Capacity output	Rs x 10^9 of 1970
C	Consumption	Rs x 10^9 of 1970
CP	Private consumption	Rs x 10^9 of 1970
CG	Government consumption	Rs x 10^9 of 1970
TX	Tax	Rs x 10^9 of 1970
IG	Government investment	Rs x 10^9 of 1970
I	Total investment	Rs x 10^9 of 1970
IF	Gross fixed investment	Rs x 10^9 of 1970
IR	Investment for the replacement of depreciated capital stock	Rs x 10^9 of 1970
JAG	Investment in the agricultural sector	Rs x 10^9 of 1970
INA	Investment in the nonagricultural sector	Rs x 10^9 of 1970
X	Exports	Rs x 10^9 of 1970
M	Imports	Rs x 10^9 of 1970
M_{0-9}	Imports of goods of SITC[b] sectors 0 to 9	Rs x 10^9 of 1970
M_{245-9}	Nonfuel imports of goods	Rs x 10^9 of 1970
F	Foreign aid	Rs x 10^9 of 1970
*F$**	Foreign aid	current U.S. $ x 10^9
*TFP$*B*	Private transfers to India	current U.S. $ x 10^9
N	Population	x 10^6
NU	Urban population	x 10^6
FREL	Fraction of villages supplied with electricity	x 10^3

Appendix B continued.

Symbol	Variable	Unit
PCOAL	Capital required for coal	Rs of 1970
FOILD	Fraction of oil domestically produced	–
ET	Total energy	10^6 tce, 5,000 kcal/kg
EC	Commercial energy	10^6 tce, 5,000 kcal/kg
ENC	Noncommercial energy	10^6 tce, 5,000 kcal/kg
EEL	Electrical energy	10^6 tce, 5,000 kcal/kg
EKW	Power capacity required	kW x 10^6
TCOAL	Total annual coal production, including coal required for electricity generation	tons x 10^6
OIL	Oil requirement	tons x 10^6
OILD	Domestically produced oil	tons x 10^6
OILM	Imported oil	tons x 10^6
KE	Capital for energy	Rs x 10^6 of 1970
YDPC	GDP, per capita	Rs of 1970
CPPC	Private consumption, per capita	Rs of 1970
CG	Government consumption, per capita	Rs of 1970
ETPC	Total energy, per capita	tce, 5,000 kcal/kg
ECPC	Commercial energy, per capita	tce; 5,000 kcal/kg
EELPC	Electrical energy, per capita	tce, 5,000 kcal/kg

[a]The symbols presented here differ slightly from those given in the text.
[b]SITC is the abbreviation of Standard International Trade Classification.

Appendix C

CLARIFICATION OF ENERGY CONSUMPTION DATA IN INDIA

Because of the conventions used in India, there is often a confusion about India's data on energy use. There are errors in the Fuel Policy Committee Report in India and in the reports of the United Nations. Therefore, we have attempted to clear up the confusion.

FUEL POLICY COMMITTEE (FPC) REPORT

Electricity consumption should be the same in coal replacement units as in coal equivalent units (tce). But electricity in terms of coal equivalent units should have the relation

$$1{,}000 \text{ kWh} = 0.172 \text{ tce (Indian coal with 5,000 kcal/kg)}\ .$$

If, however, one considers the efficiency factor on the basis of that of 1970, when 17×10^6 tons of coal were used to generate 28×10^9 kWh of electricity, then, in terms of coal consumed, 1,000 kWh = 0.6 tce. The FPC equation, 1,000 kWh = 1 tce, is, therefore, not used. For this reason our figures for energy consumption in India, especially for commercial energy, are lower than in the FPC.

WORLD ENERGY SUPPLIES OF THE UNITED NATIONS

World Energy Supplies (WES) takes the original units of each resource and multiplies them by the appropriate calorific content to obtain coal equivalent units. However, in doing so, the fact that coal in India has 5,000 kcal/kg is not considered, whereas the WES data takes the calorific value of coal to be 7,000 kcal/kg. India is, therefore, reported to have a higher energy consumption than it has in reality. The conventions used in stating energy consumption at different points in time may be seen in Tables D.1 to D.3.

Appendix D

THE DETAILED RESULTS OF SCENARIOS

TABLE D.1 Lower incremental capital/output ratio in nonagriculture.

	1975	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030	1,RATE	2,RATE
YA/YD	0.42	0.36	0.32	0.29	0.26	0.23	0.22	0.22	0.23	0.22	0.20	0.18	-2.33	-1.48
YD	457.79	606.76	794.90	1027.54	1329.03	1727.48	2093.94	2420.34	2701.09	3286.73	4116.41	5277.42	5.46	4.55
YA	190.83	221.22	256.45	297.30	344.65	399.55	463.18	536.96	622.48	721.63	836.56	969.81	3.00	3.00
YNA	231.23	336.52	471.85	642.95	872.69	1181.16	1452.39	1676.48	1846.81	2281.90	2922.83	3850.74	6.74	5.25
C	361.45	492.45	635.05	811.85	1059.11	1342.95	1621.58	1872.22	2090.23	2538.92	3171.43	4051.97	5.16	4.39
CP	326.00	419.53	538.43	686.08	875.68	1129.37	1357.02	1563.92	1743.73	2124.53	2654.29	3389.95	5.07	4.34
CG	53.45	72.93	96.26	125.13	163.34	212.83	264.73	308.40	345.80	412.22	514.72	661.23	5.68	4.68
TX	64.90	89.22	116.30	154.30	201.93	263.61	328.32	362.75	429.37	512.17	639.95	822.58	5.76	4.72
TG	33.40	43.32	55.20	69.91	89.37	114.58	141.02	163.26	182.31	216.14	268.35	342.97	5.05	4.33
I	85.43	122.26	167.30	221.07	289.78	378.20	449.53	501.87	533.90	648.95	819.32	1064.78	6.24	4.74
IF	74.65	106.13	147.77	203.06	275.36	359.96	426.97	476.71	507.91	618.75	781.19	1012.42	6.53	4.87
IAG	14.65	16.75	23.51	29.02	35.41	42.82	51.41	61.37	72.92	86.30	101.82	119.81	4.39	3.90
INA	52.00	76.76	109.49	153.74	212.59	281.94	332.59	367.45	384.73	472.16	602.71	791.43	7.00	5.07
INV	9.16	16.13	19.91	18.53	14.32	18.04	22.70	25.30	26.01	30.21	38.62	52.85	2.75	3.24
IR	7.41	10.61	14.78	20.31	27.55	36.04	42.68	47.66	50.83	61.98	78.22	101.25	6.53	4.87
X	19.71	25.15	32.10	40.97	52.29	66.73	85.17	108.70	138.73	177.06	225.98	288.41	5.00	5.00
PX	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	00.00	00.00
PM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	00.00	00.00
F	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	00.00	00.00
TFP	2.00	3.60	3.97	4.39	4.85	5.00	5.00	5.00	5.00	5.00	5.00	5.00	3.73	1.68
YF	0.06	0.34	0.62	0.90	1.18	1.46	1.74	2.02	2.31	2.59	2.87	3.15	13.92	7.59
M	26.87	33.10	38.71	45.01	52.11	59.58	62.45	62.44	60.79	75.59	96.64	126.18	3.24	2.85
PMOIL	571.20	630.65	696.29	768.76	848.77	937.11	1034.65	1142.34	1260.00	1260.00	1260.00	1260.00	2.00	1.45
MOIL	7.08	5.32	8.64	12.91	17.65	23.89	36.93	52.46	68.86	87.41	109.54	135.48	4.99	5.51
M245-9	14.63	20.42	24.15	26.75	29.93	33.47	29.92	24.21	18.08	21.61	28.67	40.70	3.37	1.88
YDPC	745.69	889.02	1057.30	1250.55	1490.72	1804.06	2050.66	2241.03	2382.08	2778.98	3355.28	4165.79	3.60	3.18
CPPC	534.43	614.69	715.80	834.70	982.30	1179.69	1328.85	1447.95	1537.87	1796.72	2163.56	2675.72	3.22	2.97
CGPC	87.11	106.85	127.89	152.09	183.21	222.16	259.27	285.55	304.85	348.26	419.18	521.79	3.82	3.31
ETPC	0.50	0.55	0.59	0.64	0.68	0.74	0.77	0.80	0.81	0.86	0.92	1.00	1.53	1.25
FCPC	0.18	0.24	0.30	0.36	0.43	0.50	0.55	0.59	0.62	0.68	0.76	0.85	4.17	2.85
FNCPC	0.32	0.31	0.29	0.27	0.25	0.23	0.22	0.20	0.19	0.18	0.16	0.15	-1.29	-1.42
ELLPC	0.02	0.03	0.04	0.05	0.07	0.08	0.09	0.10	0.10	0.11	0.13	0.14	5.91	3.71
ET	309.46	374.03	445.43	522.78	608.94	706.32	789.02	859.28	917.29	1012.97	1127.71	1262.54	3.36	2.59
EC	111.25	163.51	226.90	299.35	363.32	482.55	566.31	638.87	700.14	804.41	929.41	1075.90	6.05	4.21
ENC	198.14	210.52	218.71	223.68	225.63	223.95	222.67	220.40	217.28	208.84	198.50	186.74	0.49	-0.11
EIL	11.68	19.79	30.63	43.64	58.81	76.67	91.51	104.04	114.19	132.01	153.53	178.98	7.82	5.09
NEL	99.52	143.72	196.37	255.66	324.53	406.03	474.75	534.82	586.04	672.62	776.06	896.99	5.79	4.08
OIL	20.40	24.43	33.39	43.51	55.17	69.05	80.70	90.92	99.64	114.37	131.95	152.50	5.00	3.73
OILD	8.00	16.00	21.00	26.74	34.13	43.56	45.00	45.00	45.00	45.00	45.00	45.00	7.01	3.19
OILM	12.39	8.43	12.40	16.78	21.04	25.50	35.70	45.92	54.65	69.38	86.95	107.51	2.93	4.01
KOR	4.34	3.69	3.29	3.03	2.86	2.76	2.69	2.64	2.61	2.59	2.57	2.56	-1.80	-0.95
KORA	2.56	2.83	3.06	3.25	3.42	3.57	3.70	3.81	3.90	3.99	4.06	4.12	1.34	0.87
N	613.55	682.51	752.64	822.72	891.55	957.98	1021.06	1060.02	1134.32	1183.66	1227.93	1267.23	1.80	1.33
NU	132.39	159.65	190.85	226.15	265.66	309.45	357.55	409.97	466.77	528.01	593.79	664.30	3.45	2.98
NR	481.16	522.86	561.79	596.57	625.88	648.53	663.52	670.05	667.55	655.65	634.14	602.93	1.20	0.41
FREL	287.17	428.20	581.96	721.28	827.90	899.42	943.26	968.65	982.89	990.72	994.99	997.30	4.67	2.29

TABLE D.2 Higher agricultural growth rate and lower incremental capital/output ratio.

	1975	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030	1.RATE	2.RATE
YA/YD	0.42	0.39	0.36	0.33	0.31	0.29	0.27	0.25	0.26	0.26	0.25	0.24	-1.54	-1.00
YD	462.66	613.10	809.46	1055.24	1305.71	1808.60	2368.74	3021.77	3547.51	4357.44	5449.93	6932.35	5.62	5.05
YA	194.55	236.70	287.98	350.37	426.28	518.64	631.00	767.71	934.03	1136.40	1382.60	1682.14	4.00	4.00
YNA	229.76	326.83	454.79	617.21	842.51	1137.61	1530.98	1994.05	2309.93	2846.16	3594.99	4651.60	6.61	5.62
C	364.38	499.77	648.79	835.37	1088.26	1408.84	1840.08	2335.53	2736.33	3356.11	4191.36	5314.89	5.33	4.89
CP	330.90	426.67	552.28	709.03	920.78	1189.62	1550.46	1958.33	2293.47	2818.68	3518.61	4464.39	5.25	4.84
CG	53.55	73.10	96.56	126.72	167.04	219.42	288.02	376.72	443.60	537.37	671.89	852.80	5.80	5.16
TX	65.06	89.44	118.68	156.27	206.54	271.83	357.35	467.92	551.29	668.18	835.88	1061.39	5.89	5.21
IG	33.58	44.23	56.98	73.27	94.89	122.82	159.21	206.08	242.09	292.11	363.26	458.44	5.32	4.87
I	83.51	122.28	169.21	226.42	301.65	397.15	521.61	661.59	753.40	921.65	1154.37	1479.19	6.44	5.36
IF	74.48	108.31	152.31	213.13	286.96	376.89	497.36	629.25	714.97	875.51	1097.61	1403.86	6.70	5.48
IAG	20.05	27.64	36.87	48.10	61.77	78.39	98.61	123.22	153.16	189.59	233.90	287.82	5.60	4.96
INA	46.98	69.84	100.21	143.71	197.00	260.69	349.59	443.35	489.76	598.34	754.04	973.02	7.09	5.67
INV	8.98	13.97	16.90	13.14	14.55	20.08	25.02	32.59	38.36	46.12	57.33	76.40	3.27	3.97
IH	7.45	10.83	15.23	21.31	28.73	37.68	49.78	62.94	71.46	87.55	109.77	140.24	6.70	5.48
X	19.71	25.15	32.10	40.97	52.29	66.73	85.17	108.70	138.73	177.06	225.98	288.41	5.00	5.00
PX	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	00.00	00.00
PM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	00.00	00.00
F	5.52	6.40	7.42	8.60	9.97	11.55	13.39	15.53	18.00	20.87	24.19	28.04	3.00	3.00
TFP	2.00	3.60	3.97	4.39	4.85	5.00	5.00	5.00	5.00	5.00	5.00	5.00	3.73	1.68
YF	0.06	0.36	0.72	1.13	1.61	2.17	2.81	3.56	4.42	5.43	6.59	7.94	15.73	9.42
M	27.02	34.10	40.65	48.00	56.02	64.81	74.72	83.04	82.15	97.44	119.92	152.14	3.56	3.19
PMOIL	571.20	630.65	696.29	768.76	848.77	937.11	1034.65	1142.34	1260.00	1260.00	1260.00	1260.00	2.00	1.45
MOIL	7.18	5.41	8.70	12.90	18.39	24.15	30.68	41.05	60.04	79.97	102.91	128.85	4.97	5.39
M245-9	14.62	20.66	25.51	28.96	32.74	37.17	43.04	46.39	38.92	42.34	50.24	64.15	3.80	2.73
YDPC	750.67	898.29	1075.49	1282.06	1554.77	1887.28	2323.24	2798.78	3126.43	3681.33	4439.80	5469.03	3.76	3.68
CPPC	539.21	625.14	733.72	861.36	1033.28	1241.59	1520.04	1813.68	2021.24	2381.39	2866.17	3521.13	3.39	3.47
CGPC	87.28	107.11	128.30	154.02	187.36	229.04	282.08	348.81	391.07	453.99	547.18	672.97	3.93	3.78
ETPC	0.50	0.54	0.58	0.63	0.68	0.73	0.79	0.84	0.87	0.92	0.98	1.06	1.48	1.36
FCPC	0.18	0.24	0.30	0.36	0.43	0.50	0.58	0.66	0.70	0.76	0.84	0.93	4.14	3.00
FNCPC	0.32	0.30	0.28	0.26	0.24	0.22	0.20	0.19	0.17	0.16	0.15	0.13	-1.44	-1.60
FELPC	0.02	0.03	0.04	0.05	0.07	0.08	0.09	0.11	0.11	0.12	0.14	0.15	5.80	3.83
ET	309.07	370.80	439.98	515.30	602.42	697.25	804.27	910.72	987.72	1089.84	1208.05	1344.15	3.31	2.71
EC	112.21	164.28	227.30	299.09	386.20	483.07	595.78	707.69	790.21	901.27	1029.58	1176.32	6.01	4.36
ENC	196.84	206.52	212.66	216.08	216.34	214.10	208.90	203.11	197.38	188.58	174.61	167.60	0.34	-0.29
EEL	11.75	19.70	30.25	42.61	58.21	75.17	94.81	113.94	127.32	145.72	167.11	191.71	7.71	5.21
NEI	100.43	144.57	197.03	256.17	328.10	407.86	501.20	593.79	662.80	755.57	862.56	984.38	5.77	4.24
OIL	20.58	24.58	33.49	43.53	55.79	69.33	85.23	100.94	112.66	128.45	146.65	167.31	4.98	3.88
OILD	8.00	16.00	21.00	26.74	34.13	43.56	55.59	65.00	65.00	-65.00	65.00	65.00	7.01	3.86
OILM	12.58	8.58	12.49	16.78	21.67	25.78	29.65	35.94	47.65	63.46	81.66	102.28	2.91	3.86
KOR	4.35	3.73	3.33	3.07	2.89	2.77	2.70	2.64	2.61	2.58	2.57	2.55	-1.79	-0.97
KORA	2.58	2.92	3.20	3.43	3.62	3.78	3.91	4.01	4.10	4.17	4.23	4.28	1.54	0.93
N	613.55	682.51	752.64	822.72	891.55	957.98	1021.06	1080.02	1134.32	1183.66	1227.93	1267.23	1.80	1.33
NU	132.39	159.65	190.85	226.15	265.66	309.45	357.55	409.97	466.77	528.01	593.79	664.30	3.45	2.98
NR	481.16	522.86	561.79	596.57	625.88	648.53	663.52	670.05	667.55	655.65	634.14	602.93	1.20	0.41
FREL	287.17	428.20	581.96	721.28	827.90	899.42	943.26	968.65	962.89	990.72	994.99	997.30	4.67	2.29

TABLE D.3 Increasing aid, higher agricultural growth rate, and lower incremental capital/output ratio.

	1975	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030	1.RATE	2.RATE
YA/YD	0.42	0.36	0.31	0.27	0.23	0.20	0.17	0.15	0.12	0.11	0.09	0.07	-2.95	-3.08
YD	463.82	661.57	924.82	1303.59	1851.45	2620.03	3688.45	5264.77	7510.89	10600.69	15282.24	22441.72	7.17	7.31
YA	194.55	236.70	287.98	350.37	426.28	518.64	631.00	767.71	934.03	1136.40	1382.60	1682.14	4.00	4.03
YNA	231.92	371.16	558.78	843.77	1266.05	1878.19	2739.46	4042.69	5929.12	8546.54	12572.19	18805.10	8.73	8.32
C	362.82	497.22	681.77	944.35	1327.37	1864.72	2613.94	3726.78	5299.10	7469.26	10761.32	15796.64	6.77	7.10
CP	309.42	419.88	571.13	788.11	1103.00	1544.73	2158.77	3070.19	4356.71	6134.47	8834.27	12960.97	6.64	7.03
CG	53.17	77.52	110.20	156.79	225.27	321.74	455.54	655.41	943.32	1336.28	1928.15	2835.53	7.47	7.50
TX	96.88	142.41	203.52	290.63	418.69	599.07	849.26	1222.98	1761.34	2496.12	3602.83	5299.51	7.56	7.55
IG	46.58	65.87	91.65	128.17	181.58	256.53	360.21	514.59	736.52	1039.01	1493.83	2190.13	7.06	7.25
I	108.93	173.12	252.27	364.19	522.83	741.93	1040.03	1483.21	2115.92	2987.44	4321.05	6380.89	7.98	7.68
IF	93.91	148.74	229.90	305.53	496.04	703.26	987.24	1409.52	2008.70	2837.21	4105.38	6064.73	8.39	7.87
IAG	29.05	27.64	36.87	48.10	61.77	78.39	98.61	123.22	153.16	189.59	233.90	287.82	5.60	4.96
INA	64.47	106.23	170.07	262.20	383.68	552.94	789.70	1146.99	1653.85	2361.80	3456.01	5166.97	8.98	8.30
INV	15.26	24.31	22.71	18.85	27.15	38.98	52.39	72.93	107.02	151.19	217.91	320.20	3.82	5.69
IR	9.39	14.87	22.99	34.52	49.55	70.23	98.71	141.03	200.81	283.61	410.40	606.33	8.38	7.87
X	20.08	28.17	39.50	55.41	77.71	108.99	152.87	214.40	300.71	421.77	591.55	829.68	7.00	7.00
PX	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	00.00	00.00
PM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	02.00	00.00
F	5.52	6.40	7.42	8.60	9.97	11.55	13.39	15.53	18.00	20.87	24.19	28.04	3.00	3.00
TFP	2.00	3.60	3.97	4.39	4.85	5.00	5.00	5.00	5.00	5.00	5.00	5.00	3.73	1.68
YF	0.06	0.35	0.72	1.13	1.61	2.17	2.81	3.56	4.42	5.43	6.59	7.94	15.73	9.42
M	27.42	37.12	47.70	60.89	77.23	97.54	123.82	158.53	206.49	278.97	391.03	561.23	5.21	5.64
PHOIL	571.20	630.65	696.29	768.76	848.77	937.11	1034.65	1142.34	1260.00	1260.00	1260.00	1260.00	2.00	1.45
MOIL	6.16	5.41	10.16	17.05	26.49	38.30	52.51	70.21	90.10	130.40	178.27	234.63	7.58	6.84
M2#5-9	15.92	24.64	30.05	36.25	44.25	55.05	70.12	92.73	124.96	164.91	233.22	344.34	5.09	5.75
YDPC	756.92	969.06	1230.11	1583.86	2075.83	2732.98	3607.20	4875.55	6620.13	8955.01	12446.20	17712.79	5.27	5.90
CPPC	504.69	614.95	759.42	957.27	1236.16	1610.65	2113.88	2843.81	3839.99	5181.38	7193.53	10227.91	4.75	5.62
CGPC	86.65	113.57	146.42	190.57	252.67	335.85	446.14	606.84	831.61	1128.94	1570.24	2237.58	5.57	6.09
EIPC	0.50	0.55	0.61	0.66	0.75	0.84	0.93	1.04	1.16	1.30	1.46	1.65	2.12	2.22
ECPC	0.17	0.24	0.32	0.41	0.51	0.62	0.73	0.87	1.01	1.16	1.34	1.55	5.38	4.14
ENCPC	0.33	0.31	0.29	0.27	0.24	0.22	0.20	0.18	0.16	0.14	0.12	0.11	-1.61	-2.03
EELPC	0.02	0.03	0.04	0.06	0.08	0.10	0.12	0.14	0.17	0.20	0.23	0.27	7.18	5.07
ET	303.60	376.70	459.03	556.21	671.05	801.88	949.46	1123.70	1319.72	1535.53	1792.47	2097.11	3.96	3.58
EC	102.16	164.69	241.96	337.62	455.32	592.14	748.56	934.36	1142.64	1371.50	1642.78	1962.23	7.28	5.52
ENC	201.60	211.94	217.27	218.43	215.52	209.44	200.81	189.53	177.03	163.92	149.61	134.84	0.15	-0.73
EEL	10.74	19.98	32.80	49.51	70.51	95.03	122.96	155.99	192.79	233.09	280.92	337.27	9.11	6.47
NEL	91.52	144.65	209.26	287.97	384.62	496.88	625.57	778.55	949.84	1138.30	1361.76	1624.88	7.00	5.37
OIL	18.78	24.58	35.59	48.94	65.36	84.44	106.35	132.38	161.48	193.50	231.48	276.21	6.20	5.01
OILD	8.00	16.00	21.00	26.74	34.13	43.56	55.59	70.95	90.00	90.00	90.00	90.00	7.01	4.50
OILM	10.78	8.58	14.59	22.19	31.21	40.87	50.75	61.46	71.49	103.49	141.48	186.21	5.47	5.32
KOR	4.28	3.55	3.13	2.89	2.75	2.66	2.61	2.57	2.55	2.53	2.52	2.52	-1.88	-0.96
KORA	2.58	2.92	3.20	3.43	3.62	3.78	3.91	4.01	4.10	4.17	4.23	4.28	1.54	0.93
N	613.55	682.51	752.64	822.72	891.55	957.98	1021.06	1080.02	1134.32	1183.66	1227.93	1267.23	1.80	1.33
NU	132.39	159.65	190.85	226.15	265.66	309.45	357.55	409.97	466.77	528.01	593.79	664.30	3.45	2.98
NR	481.16	522.86	561.79	596.57	625.88	648.53	663.52	670.05	667.55	655.65	634.14	602.93	1.20	0.41
FREL	287.17	428.20	581.96	721.28	827.90	899.42	943.26	968.65	982.89	990.72	994.99	997.30	4.67	2.29

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ABSTRACTS OF RELATED PUBLICATIONS ON ENERGY

Häfele, W., and W. Sassin, Application of Nuclear Power Other Than for Electricity Generation. IIASA Research Report RR-75-40, November 1975.
Proceedings of the European Nuclear Conference on Nuclear Energy Maturity held in Paris, 21–25 April 1975, Pergamon Press, Oxford, 1976, pp. 107–119.

Primary energy shares and the end use of energy are considered first, since the applications of nuclear power other than for electricity generation have to fit into these constraints. The most immediate application is to various industries. Figures are given for the FRG and the UK; the topic of district heating is touched upon. A more detailed consideration of the growing importance of secondary energy as a consumer-oriented highly specialized energy form points to gaseous fuels. For expediting the substitution of fossil primary energy for heating purposes, hydrogen produced electrolytically from offpeak electric power of nuclear stations, and its possible market share, are considered. Truly large-scale H_2 production via thermolysis as a key to a mainly nuclear-based energy scenario leads to the long term aspects of the other applications of nuclear energy. The deployment of large scale fuel cycles is considered for an asymptotic scenario where nuclear fuels meet the entire primary energy demand. This enhances the aspect of fuel cycle collocations and their siting; artificial islands come in here. The reasoning culminates in decision trees for the deployment of nuclear power in particular and advanced energy systems in general.

Häfele, W., and W. Sassin, Energy Strategies. IIASA Research Report RR-76-8, March 1976.
Plenary Lecture at the Third General Conference of the European Physical Society on Energy and Physics, held in Bucharest, Romania, 9–12 September 1975. Energy, Vol. I, 1976, pp. 147–163.

The amount of fossil energy reserves and resources suggests a transition to an energy supply system that is based on a quasi-infinite fuel supply. Several options exist for this transition, such as the nuclear breeder or solar power. Strategies for transitions have to meet a certain demand for energy. A simple but global scenario is given for such energy demand with emphasis on low demand in conjunction with fossil fuels. Consideration is given to the constraints of such fossil energy production and emphasis is put on the CO_2 problem. This allows a rough understanding of the time scale of such transitions. In view of the timing of the transition the various options for quasi-infinite supplies of energy are considered and priorities of a number of physics tasks are conceived.

Häfele, W., and W. Sassin, The Global Energy System. Annual Reviews of Energy, Vol. 2, J.M. Hollander (ed.). Annual Reviews Inc., Palo Alto, Ca., 1977.
Reproduced in Selected Articles from IIASA, Laxenburg, Austria. Behavioral Science, Vol. 22, No. 3, 1979, pp. 169–189.

A global energy system is conceptualized and analyzed: the energy distributor subsystem of the worldwide supranational system. Its many interconnections are examined and traced back to their source to determine the major elements of this global energy system. Long-term trends are emphasized. The analysis begins with a discussion of the local systems that resulted from the deployment of technology in the mid-nineteenth century, continues with a description of the global system based on oil that has existed for the past two decades, and ends with a scenario implying that an energy transition will occur in the future in which the use of coal, nuclear, and solar energy will predominate. A major problem for the future will be the management of this energy transition. The optimal use of global resources and the efficient management of this transition will require a stable and persistent global order.

Häfele, W., J.P. Holdren, G. Kessler, and G.L. Kulcinski, Fusion and Fast Breeder Reactors. IIASA Research Report RR-77-8, November 1976 (revised July 1977).

In a two-year study, a team of researchers has evolved a comparison of fast fission breeders and D–T fusion reactors, as both nuclear reactors allow, at least in principle, for an essentially unlimited supply of large amounts of energy. In this report, resources for the two reactor types are briefly reviewed, and their present status is discussed in terms of scientific, engineering, and commercial feasibility. Reference reactor systems are the German/Belgian/Dutch fast breeder prototype SNR 300, a liquid-metal fast breeder reactor, and the deuterium–tritium TOKAMAK fusion reactor concept. Radioactive inventories of reactor economies are discussed in length, with emphasis on the biological hazard potential index for comparing relative hazards on pathways (inhalation, ingestion) and injuries to the human body. The safety problem involved in normal operating losses and exposure centers around releases of tritium in fusion, and around alpha-emitters, iodine-129, and krypton in fission. Design basis accidents as well as acts of war, sabotage, and hypothetical events are dealt with under non-routine releases. Safeguards are analyzed in the nonproliferation context. Materials – a problem more severe for fusion than for fission – and the impact of radiation damage are an important chapter. Reactor strategies for commercialization are evaluated in terms of timing of related programs and their funding. Great care has been taken to appropriately introduce the problem of nuclear energy and to put the conclusions in their proper perspective.

Williams, J., (ed.), Carbon Dioxide, Climate and Society. The Pergamon Press – IIASA Conference Proceedings Series, Vol. 1, 1978.

This volume, the proceedings of an IIASA workshop held in February 1978, examines the environmental and climatic problems associated with increased atmospheric CO_2 concentrations and the serious constraints this could have on the use of fossil fuels as a vital energy source. The IIASA Energy Systems Program is studying global aspects of energy systems, concentrating on a time period 15 to 50 years from now. The study therefore considers energy resources and demands, options, strategies, and constraints. One constraint on an energy system is its potential impact on climate. The IIASA Energy and Climate Subtask, which is supported by the United Nations Environment Programme (UNEP), is studying the possible impact on global climate of the three major medium- to long-term energy options: nuclear, fossil fuel, and solar energy conversion systems. A workshop was held at IIASA in February 1978, cosponsored by the World Meteorological Organization (WMO), UNEP, and the Scientific Committee on Problems of the Environment (SCOPE), to discuss questions associated with carbon dioxide (CO_2) produced by the combustion of fossil fuels, its impact on climate and environment, and the implications of present knowledge on these questions for energy strategies. The Workshop considered three major aspects of the "the CO_2 problem." First, the biogeochemical carbon cycle was discussed as a background for predicting future atmospheric concentrations of CO_2 given a knowledge of inputs. Second, the present state of knowledge regarding the impacts of increased atmospheric CO_2 concentrations on climate and environment was examined. Third, the implications of our present knowledge (and lack of knowledge) of the first two aspects with regard to decisionmaking on energy strategies were analyzed. The material presented in the Proceedings forms the basis for a continuing study of the climate constraints of the fossil fuel option and a comparison of the options.

Marchetti, C., On 10^{12}: A Check on Earth Carrying Capacity for Man. IIASA Research Report RR-78-7, May 1978.
Energy, Vol. 4, 1979, pp. 1107–1117.

Much has been said about the carrying capacity of the Earth and with most contradictory results, as the arguments have too often been used in the service of prejudices. In this paper we have made a static cross-section of a world very heavily populated by present standards; examined with a system view the level of basic necessities plus luxuries for this population; and indicated the technology to satisfy them. Where problems of a global level appeared, a geoengineering solution has been sketched. The result of this analysis is that, from a technological point of view, a trillion people can live beautifully on the Earth, for an unlimited time, and without exhausting any primary resource, and without overloading the environment. The global view of the problems and of their solutions makes the difference, and shows that most of the perceived physical limits to growth stem from an inappropriate frame of reference. Although our result should by no means be interpreted as an invitation to multiply, it does cast some doubt on the reliability of resource investigations within too narrow assumptions about the adaptability of man to changing conditions and transfers the problem of the limits to growth where it belongs: to the areas of sociology, politics, and ethics.

Häfele, W., and W. Sassin, Energy Options and Strategies for Western Europe. Science, Vol. 200, 1978, pp. 164–167.

Western Europe, now largely dependent on oil imports, has to prepare for strong competition for oil and energy imports in general before the year 2000. The more unlikely it is for Western Europe to secure from outside rich supplies of coal or uranium at readily acceptable economic and political conditions, the more serious this competition becomes. Even exceptionally low projections of economic growth and optimistic assumptions about energy conservation urgently call for vigorous and simultaneous development of indigenous coal and nuclear sources, including the breeder. Long-term contracts for the possession and deployment of foreign oil, gas, and coal deposits are mandatory and should be negotiated in view of the possible aggravation of north–south confrontation.

Grenon, M., (ed.), Future Coal Supply for the World Energy Balance. The Pergamon Press–IIASA Conference Proceedings Series, Vol. 6, 1979.

This volume is a collection of the papers presented at the Third IIASA Conference on Energy Resources, November 28–December 2, 1977. Over half of the papers in this volume deal with the most recent technical developments in the supply of coal and the situation as regards future world coal supply. Topics covered include resources assessment, mining techniques, coal transportation, underground coal gasification and coal conversion processes. Other papers analyze the coal potential in more than 12 countries. Finally, some global problems, such as the CO_2 question, are considered.

Marchetti, C., On Energy and Agriculture: From Hunting–Gathering to Landless Farming. IIASA Research Report RR-79-10, December 1979.
The paper was presented at the conference, Science and Technology for Agriculture, that took place in Bari, Italy, October 27–29, 1978.

An energy analysis of agricultural practices shows very coherent patterns of evolution from the Neolithic Age up to this century. All technical advances were in fact exploited toward intensification, and the ratio of food output to energy input was held remarkably constant over such a long stretch of time. New agricultural practices in developed countries linked to massive energy "subsidies" from fossil fuels have disrupted the trend, substantially altering these practices. Low-tillage techniques, hormonal and genetic pesticides and herbicides, nitrogen fixing in grains, and other emerging technologies satisfying this constraint are briefly described and assessed in this paper.

Häfele, W., IIASA's World Regional Energy Modeling. Futures, February 1980. This article is based on a paper presented to the Dublin International Conference on Energy Systems Analysis, 9–11 October 1979, organized by the Commission of the European Communities and the Irish National Board for Science and Technology. The full conference proceedings will be published as Energy Systems Analysis, by D. Reidel, Dordrecht, the Netherlands, 1980.

After stressing the need for, and difficulties in, long-term supranational energy-supply strategies, the author describes a high and a low scenario. Both are fairly conservative, even in their assumptions on the main variant, economic growth. Quantified for seven world regions via a set of highly iterative models, the scenarios give a conceivable energy-demand range over the next 50 years. By 2030, nuclear power may supply over 20% of the world's energy; coal, in the form of synthetic fuels, will be replacing oil. Resource allocation and trade flows will in general be restricted by production ceilings. A satisfactory world and regional long-range energy supply will depend on prudent political and economic decision making.

Niehaus, F., and E. Swaton, Public Risk Perception of Various Energy Systems. Proceedings of the European Seminar on Methods for Optimizing Protection of the Nuclear Industry, 3–5 October 1979, Luxemburg (forthcoming).

The Joint IAEA/IIASA Risk Assessment Project was formed in 1974 when IIASA was embarking on a program to study the energy supply/demand situation in a long-term time-frame. Studies of the risks attached to the various sources of energy were to be included for recommendations to decision-making organs about future energy strategies. The technical approach to risk assessment concentrates on comparisons of risks and benefits of alternative energy systems considering their total fuel cycle. The social science approach takes account of the fact that public perception of energy systems and their readiness to accept them play a major role when designing energy strategies for the future. Methods are being developed which allow both technical data and social values to be considered, and to be included in decisions on risk management.

A list of selected IIASA and external publications by the Energy Systems Program Group is available from the Publications Department, IIASA, A-2361 Laxenburg, Austria.

IIASA NEWS

Report on the Workshop on Nuclear Accident Preparedness and Management

D.C. Bull, *Management and Technology*

In January 1980, 49 participants from 19 countries assembled at IIASA at the invitation of the IIASA Risk Group to discuss nuclear safety strategies. Twenty-five papers were presented on a wide range of topics, including emergency preparedness, learning from past mistakes, the philosophy of decision making, and accident management.

Several persons from the United States were present who had been directly involved with the Three Mile Island (TMI) accident, including the president of the company that owns the TMI plant, members of the Nuclear Regulatory Commission, and the head of the local Civil Defense Organization.

In the early stages of the Workshop it emerged quite clearly that those who had been involved in the TMI accident felt that they had a message: they were concerned that the rest of the world should learn from their experiences and mistakes, for the good of the nuclear industry generally and to improve its safety in particular. Their presentations and interventions contrasted with others that dealt with various national policies, regulations, and procedures. The major differences among these latter national planning presentations were technical: e.g. the size of a proposed evacuation zone, or the time or dose level at which thyroid-blocking potassium iodide tablets might be distributed.

As the Workshop developed, however, it became clear that the private views of participants had been very much modified by the TMI experience and were continuing to be modified in the light of information exchange and discussions at the Workshop. National plans were in most cases under review, each country wishing to be sure that it had learned as much as possible from the TMI accident.

A break in the lecture/discussion sessions was provided by a showing of a videotape recording of the speech that College President John G. Kemeny gave to the Dartmouth College Community on his return from presiding over the Presidential Commission on the TMI accident. In this, a paragon of presentation of technical matters to a nontechnical audience, he identified the central issues as being associated with "people problems." Many of the issues that had arisen were not new, lessons from previous accidents and similar incidents had not been learned – the accident had in a sense been predicted.

David W. Fischer, a former member of the IIASA staff, now in Norway, drew a striking comparison between the details of two major – but technically disparate – accidents: the TMI accident and an oil blowout on the North Sea oil platform "Bravo." Both accidents arose as consequences of parts of the maintenance programs. The initiating event in each case involved a stuck valve, an everyday low-technology component. In both cases the accident was associated with weak organization in administrative systems, procedures, and practices. In both cases the accident was preventable. In each case, although safety plans and programs existed, they had not been supported by regular inspections, and no specific plans existed for coping with the outcome: a potential core melt in one case and a line-control blowout in the other.

While it cannot be said without argument that the TMI accident lies in the gray area of unpredicted potential accidents, what some risk analysts call the "rogue event," a paper by Professor Ott and coworkers from the FRG suggested that these rogue events can be associated with the notion that unknown types of accidents are in a sense "lurking" in certain technological systems. They elaborated this point by a statistical evaluation of designer-related accidents. The idea of attempting to quantify the concept of rogue events may have some appeal to risk analysts.

When it comes to tackling that most difficult question of learning by our mistakes, it is clear that one of the central problems has to do with communication, another with appropriate analysis of accident incidents so that the underlying lessons can be learned. On this latter topic an interesting paper by Dr. Kumamoto and colleagues from Japan described a cause–consequence data-base system that uses computer techniques to create sets of records of the underlying happenings in a series of accidental events. In this way he hopes to build up a substantial data base, both from the nuclear industry and from the petrochemical industry. His research team already has 100 records in their data base from the Kemeny report alone. This is a promising way to preserve the legacy of accidents and incidents and hence to systematize the process of industrywide learning.

In summarizing the central issues of the Workshop, John Lathrop of IIASA echoed the views of many. Various countries have different levels and types of preparedness. Major differences exist in the technical details and specifications, but some of the current plans seem to be too detailed and too involved. The TMI accident drew attention to the fact that accidents can occur where the current levels of preparedness will not be effective. It may be that this problem needs to be tackled by an increase in preparedness for the accident or alternatively by increased candor and information supplied to the public about the albeit remote possibilities of accidents. Some of the current guidelines, which are based on achieving certain threshold levels of radiation dose, may not help decision makers in the confusion of a real accident. Certainly such guidelines existed in the TMI case, but were not useful. For example, in the US there is a five man-rem threshold guideline recommending protective action. While this threshold dose was never measured, there was an apparent danger that a hydrogen bubble in the reactor could explode, perhaps leading to a major release. The dose guideline provided little guidance to the decision maker concerned about the hydrogen bubble. The lesson is that general guidelines geared to easily observed plant parameters are of more use than ones based on indirectly observable parameters.

This last point was also underlined by Harry Otway from the Joint Research Centre, Commission of the European Communities, at Ispra, who indicated that, the more detail attached to plans or systems in general, the more likely things are to go wrong. Dr. van den Heuvel, the mayor of a town in Holland, voiced the opinion that some of the detailed plans and detailed explanations were too much to impose on a population in an emergency situation; he too lent support to the idea to use simple coarse guidelines for action.

The free and open discussion of the details of the nuclear accident and of accident prevention among the nuclear community augurs well for this industry. It was heartening that some delegates to the workshop talked openly about what to do *when* the next accident occurs and did not pretend that the TMI accident would be the one exception, buried in some low probability figure. It may very well be that the public will have more confidence in the industry that has rare accidents or incidents from time to time but shows that it can handle them competently.

IIASA acted as the catalyst for this discussion by bringing together parties playing quite different roles in the nuclear industry and its interactions with society. The meeting was international, and provided the opportunity for ongoing informal contacts which will help in the rationalization of individual countries' plans and enhance cooperation in the areas where international cooperation is essential. IIASA also contributed to the Workshop by presenting an embryo systems-analytic approach to the problems raised in accident management.

The papers which were presented and the systems-analytic summary of the lessons to be learned will be published by IIASA shortly.