AN INTEGRATED ENERGY SIMULATION MODEL OF THE FEDERAL REPUBLIC OF GERMANY AS A DECISION AID FOR ANALYZING AND PLANNING THE ENERGY SYSTEM

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ABSTRACT

As a decision aid for planning the national energy system the Programme Group of Systems Analysis and Technological Development (STE) of the Nuclear Research Centre (KFA) at Jülich (Federal Republic of Germany) has developed a simulation model which integrates macroeconomic, energy demand and supply as well as environmental modules.

The structures of these four parts of the model, which are interlinked with each other, are explained in detail and the capabilities of that system for reasonable long-range planning are demonstrated by some results for alternative energy supply and conservation strategies under different economic growth rate assumptions.

I. INTRODUCTION

The world-wide energy debate, which probably will not come to a definite end within this century, has shown that there is no simple recipe for solving the outstanding questions and problems. Traditional planning instruments are no longer sufficient to deal with objectives and constraints which are not only technical or economical ones but must take into consideration the employment situation, the depletion of fossil energy reserves and the environmental impacts as well as the life style and the limited risk acceptance by the general public. The problem of planning the energy scene has become a combined technical, economical, environmental and social one.

In order to master this interdisciplinary task, new tools have to be developed for analyzing complex systems at a rather high level of aggregation and for helping decision makers to find reasonable policies.

Within the STE a framework of models, methods and data has been set up (illustration 1), which facilitates the investigation of the consequences of alternative energy strategies before making decisions. We shall not consider here the global models (1,9), as well as the models or modules for some sophisticated special aspects like net energy consumption or cost-optimal coupled production (5). We restrict ourselves to the description of the basic national model, which contains the first four modules shown in illustration 1. Illustration 2

ILLUSTRATION 1

Integrated Model - Method-Data System

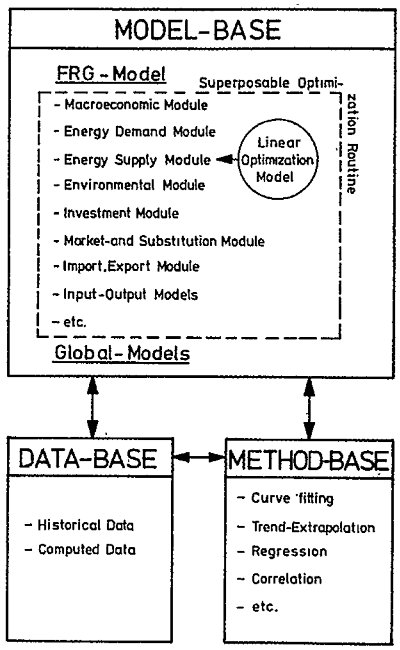
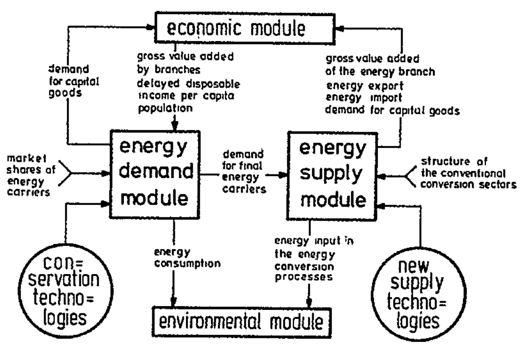


ILLUSTRATION 2

Model Structure



gives an overall view of the links between these modules, which form an interaction structure of closed-loop type.

II. THE MODEL

THE MACROECONOMIC MODULE

The aim of the macroeconomic module is to provide the necessary inputs for the energy demand module, i.e. the population size, the average disposable income per capita and the gross value added by branches. This module (2) describes the dynamic relations between the employment and population sector, the capital-stock sector, the production sector, the demand sector, and the investment sector in terms of differential equations. Though the overall gross value added is a result of the dynamic structure itself, it may be influenced by a wanted or expected economic growth rate. Thus, different scenarios may be produced with respect to the development of the economic system.

Within the employment and population sector the employees in the different economic sectors are computed as a function of the population growth and the labour force participation rate on the one hand and the capital intensity of production on the other.

The capital stock is determined by the gross investments and the depreciations.

For calculating the contributions of each production sector to the gross domestic product (GDP) a Cobb-Douglas production function is used together with capacity load factors, the production factor labour being the number of employees, the production factor capital being the size of the capital stock.

In the demand sector the final domestic and import demand for private and public consumption, investment goods and exports is determined as a function of the personal disposable income, public expenditures, investment orders and import/export quotas. The intermediate demand between the different production sectors is computed by means of time dependent input-output coefficients so as to meet the final demand.

The expected future demand, based on its past development influences the economic growth by driving the investment decisions. Since they imply orders for investment goods they change the final demand again as well as the capital stock.

THE ENERGY DEMAND MODULE

Calculating the final energy demand is done by looking at the different consumers and consumption purposes, the disaggregation following the paths of consumption down to different levels, as far as is necessary and possible (3).

At the first level one has the industry, the petrochemical sector with its non-energetic demand, the commercial sector, the private households and the transportation sector. As an example, the energy demand calculation within the industrial sectors will be shown in more detail. There we have the four main energy consumers, namely the iron-and-steel industry, the chemical industry, the industry of glass, pottery and building materials, and the engineering and other metal industry and, as a remainder, the fifth sector, all other industries.

For each industrial sector a correlation function was obtained by regression analysis of past data, back to 1950, for the total energy consumption per unit of the gross value added (GVA) of this sector. We give an example for the iron-and-steel industry. In this case, for determining the energy demand we use the correlation function between the steel production in tons of steel and the GVA (illustration 3) as well as a time series of the specific energy consumption per ton of steel (illustration 4). This total energy demand is broken down into the different energy carriers by exogeneously given market shares (illustration 5).

ILLUSTRATION 3

Regression Analysis : Iron and Steel Industry

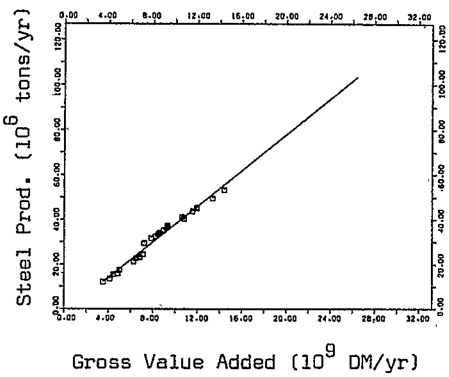


ILLUSTRATION 4

Specific Energy Consumption : Iron and Steel Industry

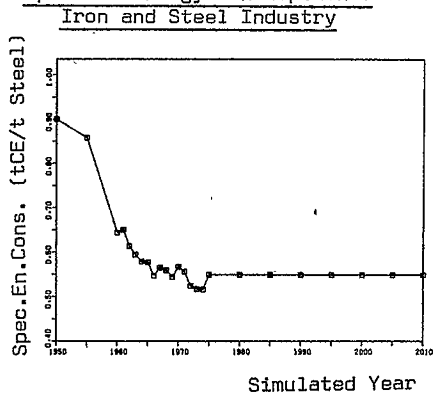


ILLUSTRATION 5

Market Shares of Energy Carriers :
Iron and Steel Industry

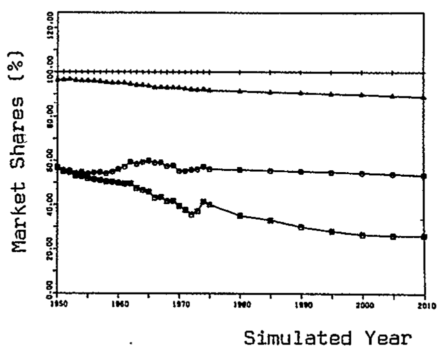
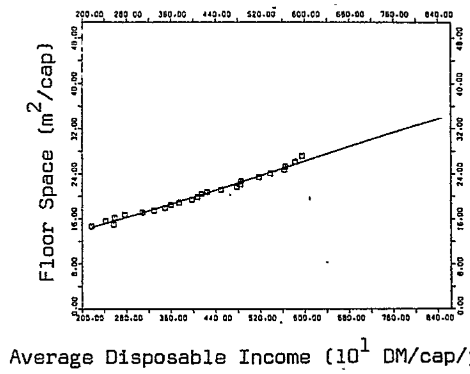


ILLUSTRATION 7

Regression Analysis : Private Households



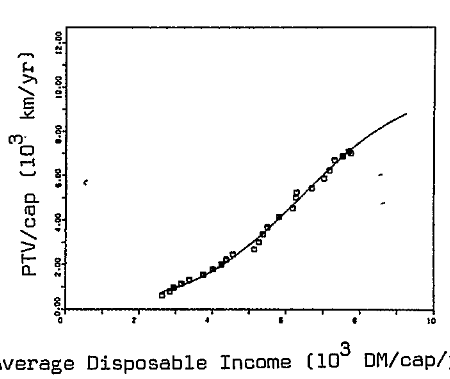
The same scheme of calculation holds for all industrial sectors, including the petrochemical sector, where the total non-energetic demand is correlated with the GVA of the chemical industry.

The energy demand for transportation distinguishes between the four systems road, rail, air and water on the one hand and goods and passenger transport on the other, the passenger transport being split up into the individual and the public parts. The transport volume is correlated with the industrial gross value added for the goods transport or with the average disposable income per capita for the passenger transport. Illustration 6 demonstrates this relationship for the individual modes of passenger transport, which shows a strong saturation tendency. The breakdown into the different transportation systems is given by structure shares and the total energy demand for each system then follows by multiplying the transport volumes with the corresponding specific energy consumptions. Again, exogeneously given market shares determine the energy demand by energy carriers.

The residential sector is the most complex subsystem on the demand side. Firstly space heating

ILLUSTRATION 6

Regression Analysis :
Individual Persons Transport Volume



as the major part is separated from the non-heating uses. The main determinants for the space heating sector are the population size and the floor area per capita, which was correlated with the average disposable income per capita. An expected saturation of 120 m^2 for the statistically average 2.4 person household led to a logistic regression curve (illustration 7).

The total floor space is sub-divided with respect to three aspects:

- the type of house (one and two family versus multi-family houses),
- the heating system (central heating versus non-central heating),
- the age (old - i.e. existing - versus new houses).

For each of these categories the shares of the energy carriers used are analysed for the past and assumptions are made according to the observed trends which may be altered as strategies or scenarios. At last, the energy demand by energy carriers is obtained by taking into consideration the specific fuel consumption of each fuel.

The remaining energy demand sectors namely non-space heating in private households, the commercial branch and the other industrial sectors, are treated in the same manner but in a more global way, because they are not so important with respect to the energy demand.

THE ENERGY SUPPLY MODULE

In order to meet the energy demand, which is taken as the actual consumption in the supply module, a flow model was constructed. This is described mathematically by a set of simultaneous equations, which is solved at discrete time steps. The main relation for each of the 14 energy carriers (index i) is the balance equation:

$$m_i+i_i-e_i-b_i+s_i=p_i=f_i+d_i+\sum_j(I_{j,i}-O_{j,i}+E_{j,i})$$

On the left hand side of the primary energy consumption (p_i) there are the indigenous production (m_i), the import (i_i), the export (e_i), the bunkering (b_i), and the net stock decrease (s_i). On the right hand side we have the final energy consumption (f_i) including the non-energetic part, the distribution losses (d_i), and the resultant of the conversion balance, i.e. the inputs ($I_{j,i}$) minus the outputs ($O_{j,i}$) plus the self consumption ($E_{j,i}$), summed up over the number of processes (index j). At present we consider 20 different conversion technologies the new ones being

- advanced nuclear reactors for electricity production (high temperature reactor and fast breeder reactor)
- nuclear and non-nuclear coal gasification of hard coal and lignite
- nuclear-thermochemical and electrolytic hydrogen production (for a strategy of forced hydrogen use as for example with direct reduction in the iron-and-steel sector)
- methanol production (for a strategy of adding methanol to motor spirit)
- central wind power stations.

In order to get a unique solution for the set of equations, additional relations between the unknown variables had to be found. Firstly there are the technical parameters of the conversion technologies. As far as possible we have formulated them in the following manner (see illustration 8 for the example cokeries; the abbreviations used in the scheme are: index j ≙ CO for cokeries; index i ≙ C for hard coal, K for coke, D for gas).

The total energy input I_j is given by the total output O_j and a coefficient QI_j, which is the reciprocal efficiency. The input is broken down into the different energy carriers by the shares $QI_{j,i}$, the sum of which equals one. In the case of coupled production the relation between the byproducts and the main product is given by factors $QO_{j,i}$ (an example for the cokeries is given in illustration 9). The self consumption is formulated as a function of the total output in the same manner as for the energy input, i.e. by an overall ratio QE_j and shares $QE_{j,i}$ for the single energy carriers. (Illustration 10 again shows the situation for the cokeries, the lower curve represents the share of gas, the remainder being coke).

Thus for each special conversion technology $1 \in j$ there remains one unknown item, the output of the main product $O_{1,k}$ with $k=k(1) \in i$. This determinant may be found by reformulating the balance equation for the energy carrier k:

$$O_{1,k}=f_k+d_k-p_k+\sum_j(I_{j,k}+E_{j,k})-\sum_{j\neq 1} O_{j,k} \,.$$

The last term represents the sum of byproducts of all other conversion processes. The distribution losses d_i and the primary energy consumption p_i for the carriers of secondary energy are correlated to other endogeneous quantities. For the details we refer to two recent studies of the STE (6,7).

The satisfaction of the demand for primary energy carriers is formulated in a different way. The inputs to the transformation sector being known now,

ILLUSTRATION 8

Informational Scheme of the Cokeries

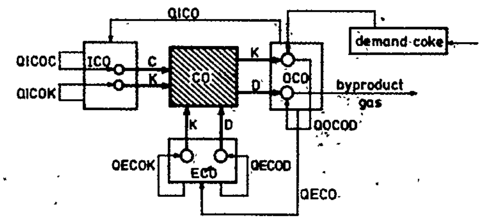


ILLUSTRATION 9

Cokeries : Gas as By-Product of Coke Production

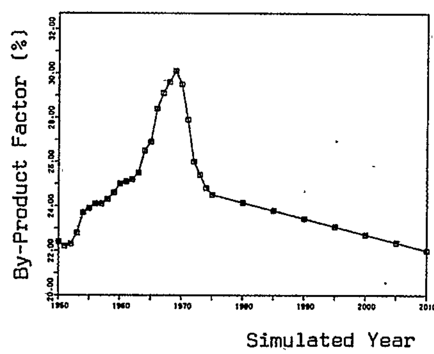
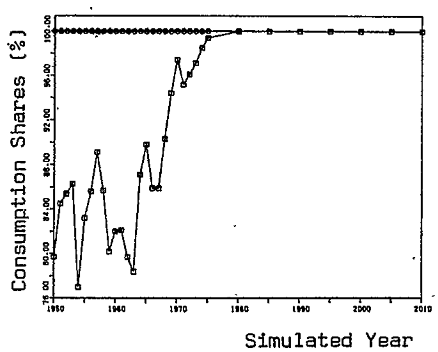


ILLUSTRATION 10

Cokeries : Structure of the Self-Consumption



the primary energy consumption is calculated as

$$p_i = f_i + d_i + \sum_j (I_{j,i} + E_{j,i}) .$$

Then the indigenous production is given by a relation of the form

$$m_i = \min (c_i, r_i, p_i \cdot q_i)$$

where c_i represents the mining capacity, r_i the domestic reserves and q_i is a factor which is greater than unity if the exports exceed the imports or less than unity otherwise.

Within a national model, it is not possible to make the imports and exports totally endogeneous. These quantities, therefore, are given as time series which are derived by the global energy models or are given as scenarios. The same holds for the bunkers and the stock changes, as long as there are no governmental regulations, such as a law requiring a national reserve of oil and oil products.

Last but not least, the contributions of the energy sector to the GDP, the investments and the labour forces are calculated. This is done by multiplying the energy production of each process with specific values, given exogeneously as time series. So, the whole loop macroeconomy-energy demand-energy supply-macroeconomy is closed.

THE ENVIRONMENTAL MODULE

The total emissions due to energy production, conversion and consumption are calculated in the environmental module, separately for the sectors and energy carriers which cause them and for the destinations air and water. Up to now we have considered nine chemical and four radioactive pollutants as well as the release of waste heat. Different environmental abatement rules and technologies are formulated and can be calculated as scenarios e.g. desulfurization techniques. The necessary investments are fed back again to the macroeconomic sector.

III. SOME RESULTS

REFERENCE CASES

In the following we show some scenarios which we elaborated by means of the integrated energy model for the Federal Republic of Germany. In order to be able to evaluate the results we constructed a hypothetical reference scenario which is based on the assumption that historical trends in the energy demand and consumption patterns persist and no new energy technologies will be implemented. As for the economic growth which is the main determinant for the energy demand and consumption it was assumed that it will follow the linear trend of the past 26 years with a slight decrease beyond 1995. This reference scenario, called historical growth scenario, or 3-2-1 case, is based on an overall economic development as shown in table 1.

TABLE 1

Average GDP-Growth Rates (% p.a.)

Time Period	3-2-1 Case (Historical Growth Scenario)	4-3-2 Case
1975-1985	3	4
1985-2000	2	3
2000-2010	1	2

The second economic growth scenario (4-3-2 case) with higher growth rates reveals the effects which the economic growth has on energy demand and supply. Economic cycles are not considered for these two scenarios as the model is conceived for long-range planning.

These global economic developments should be understood as political parameters, which characterise one of the global objectives of decision makers in the economic field. In the macroeconomic module they are further differentiated due to sectoral differences, so that the changes in the development of different economic sectors and the consequences for the energy consumption structure can be observed.

For this purpose an aggregation structure for the producing sectors was chosen which reflects the share of their energy consumption requirements within the total final energy consumption for production purposes. The iron-and-steel industry for example had a share of only 2.6% of the industrial GVA in 1975, but it consumed more than 30% of the total industrial energy demand. Thus even small absolute changes in the economic structure may cause relatively large changes in the pattern of energy demand.

As computed by the macroeconomic module the changes of the net production shares in percent between 1975 and 2010 are as follows for the 3-2-1 case, (4-3-2 case in brackets):

-7 (-21)% for the glass, pottery and building materials sector, -9 (-14)% for the iron-and-steel sector, +28 (+12)% for the chemical sector, +17 (+16)% for all other industrial sectors, -12 (-7)% for the commercial branch, and +3(-17)% for the energy branch.

At the chosen aggregation level of the producing sectors it is impossible to draw conclusions for merely economic policies from these figures. The energy consumption calculations, however, are very strongly affected.

The assumed economic development in the historical growth scenario leads, according to the results of the energy demand module, to a final energy consumption which is shown in illustration 11. The final energy demand is plotted against time and accumulated by energy carriers (from bottom to top these are: solid fuels, petroleum products, gas, electricity, district heat, hydrogen).

As mentioned above, these results have been obtained by extrapolating today's energy demand and supply

ILLUSTRATION 11

Final Energy Consumption (3-2-1 Case)

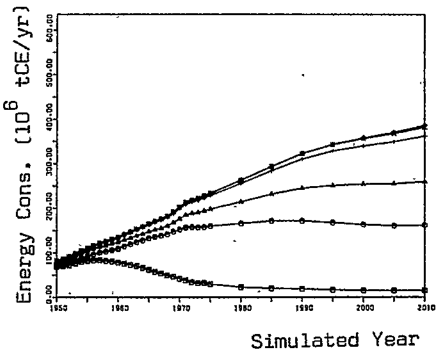


ILLUSTRATION 12

Primary Energy Consumption (3-2-1 Case)

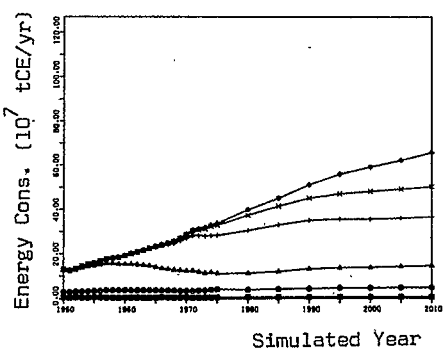
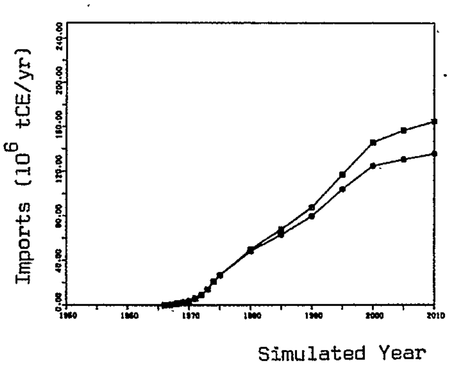


ILLUSTRATION 13

Natural Gas Imports (3-2-1 and 4-3-2 Case)



structures but taking into consideration saturation effects, e.g. for population growth, dwelling size, number of cars, etc. as well as regulations which can be foreseen to come into effect on the energy demand side, e.g. energy saving technologies like better insulation of new buildings, or on the energy supply side, e.g. no extension programmes for oil and gas fired power plants.

To provide the required amounts of final energy in the 3-2-1 case the energy supply module computed the necessary primary energy for each energy carrier as demonstrated in illustration 12 (from bottom to top - accumulated -: hydro power, lignite, hard coal, petroleum products, gas, nuclear power).

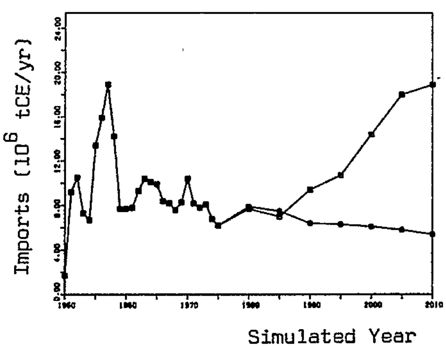
As the Federal Republic of Germany has no significant reserves of crude oil and natural gas, for the medium and long-term supply of these energy carriers there may be severe import bottlenecks as long as synthetic fuel production is not considered (like in the reference scenarios). The imports of natural gas would have to develop as shown in illustration 13 (the lower curve belongs to the 3-2-1 case, called the historical growth scenario, and the upper one to the 4-3-2 case).

It was assumed that hard coal consumption for electricity generation will nearly double by 2010. Although the corresponding domestic production is supposed to increase by 30%, additional amounts of hard coal would have to be imported as shown in illustration 14. Again the upper curve shows the 4-3-2 case and the lower one the 3-2-1 case. These quantities have already been achieved in the past so that it should be possible to obtain them.

In the following, two alternatives to the reference cases are investigated. This is easily done with a simulation model, for example by switching to new technologies on the energy demand or supply side at given market penetration rates.

ILLUSTRATION 14

Hard Coal Imports (3-2-1 and 4-3-2 Case)

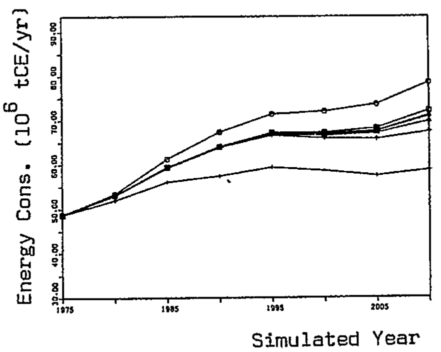


ENERGY SAVING

Next, some of the most frequently discussed possibilities for saving energy in private households will be demonstrated by showing the changes in relation to the historical growth scenario. Space heating today represents more than 80% of the private energy consumption (excluding individual passenger transportation). In illustration 15 the saving effects of some energy conservation strategies are shown. For the discussion here we pick out the most effective ones. The top curve shows the development of the energy consumption for space

ILLUSTRATION 15

Energy Conservation Strategies : Space Heating in Private Households



heating in private households without energy saving. The curve beneath demonstrates the effect of the planned insulation order for new buildings and the lowest curve the saving which would be possible if the insulation of new and old buildings would be accelerated; the reduction in specific energy consumption being 40% per house equipped. The curves in between refer to the savings which could be expected by introducing heat pumps and solar energy systems. They are of less importance because they are partially limited to one and two family houses and market penetration rates are estimated to be lower than those for enhanced insulation.

SYNTHETIC FUELS

Coal gasification is considered here as a second example for alternative model runs. It is one of the most promising new energy supply technologies for the Federal Republic of Germany. The reasons are that the development of this technology is rather advanced and that there are rather large domestic reserves of coal. The following three coal gasification strategies were chosen:

a. Gasification of lignite and hard coal by means of nuclear process heat. (Capacities per plant with a 3000 MW_{th} reactor: 395 · 10^3 m^3 SNG/h for lignite and 227 · 10^3 m^3 SNG/h for hard coal gasification)

b. Gasification of lignite and hard coal by autothermal processes (LURGI-process); capacity per plant: 312 · 10^3 m^3 SNG/h.

c. Gasification of lignite and hard coal by application of both nuclear and autothermal processes.

Table 2 shows the number of gasification plants on which the computations are based.

TABLE 2

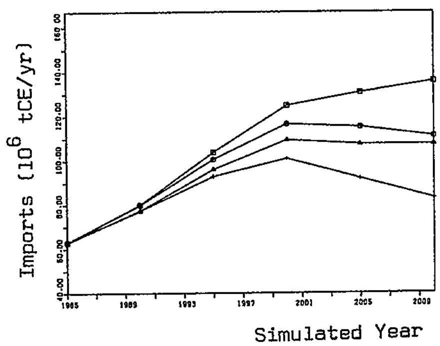
Gasification Strategies

	Number of Gasification Plants			
	Lignite		Hard Coal	
Year	autoth.	nuclear	autoth.	nuclear
1965	0	0	0	0
1990	1	0	0	0
1995	2	1	1	0
2000	3	2	3	1
2005	4	3	5	3
2010	4	4	7	6

Operating these plants as assumed in the three strategies would lead to a reduction in the calculated necessary gas imports. In illustration 16 these reductions for the three strategies are visible (c, b and a reading from the bottom) and for the historical growth case as reference (top curve).

ILLUSTRATION 16

Gasification Strategies : Natural Gas Imports



As for the additional hard coal needed for gasification purposes, we assumed that it could be imported; for lignite the Federal Republic of Germany is completely dependent on its own reserves and production capacities. The development of hard coal imports for the different strategies is shown in illustration 17. For the identification of the curves (overlapping!) we refer to the year 2010. (From bottom to top: 3-2-1 case, gasification strategies a,b,c). It can be seen that autothermal gasification processes would considerably increase

ILLUSTRATION 17

Gasification Strategies : Hard Coal Imports

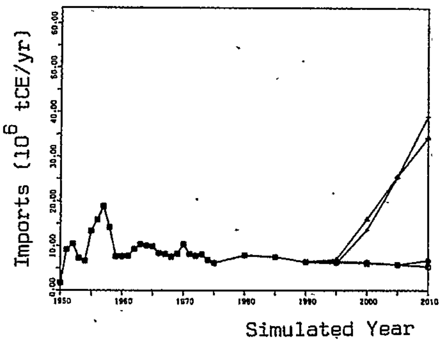


ILLUSTRATION 18

SO_x - Emissions by Different Sectors

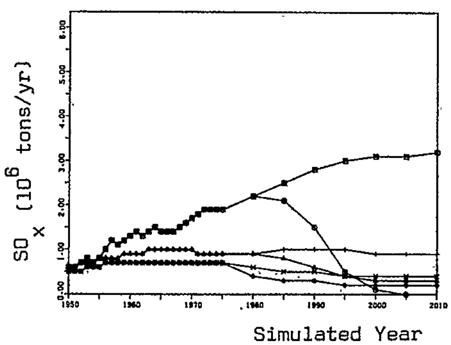
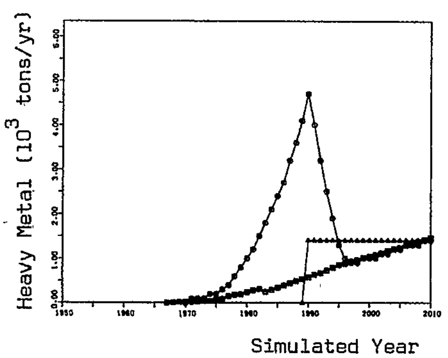


ILLUSTRATION 19

Yield of Irradiated Heavy Metal (3-2-1 Case)



the imports of hard coal.

Gasifying lignite decreases the coal input into the electrical power plants, because domestic production of lignite cannot be extended significantly in the future.

The electricity shortage could be met by nuclear power stations, the required amount of substitution being smaller in the case of nuclear gasification plants because of their by-production of electricity.

ENVIRONMENTAL ASPECTS

In illustration 18 the emissions of sulfur dioxide are plotted for the historical growth scenario, subdivided into the main sectors which cause them. (from top to bottom: the energy branch, the industry sector, the private households together with the commercial sector). The branching of the three curves in the future demonstrates the effects of additional desulfurization techniques. It is evident that the energy branch particular, when not operating desulfurization appliances, would cause unacceptable emissions to the environment.

Next, the yield of irradiated heavy metal leaving the nuclear power plants per year (as expected in the historical growth scenario) and its reduction by a planned reprocessing plant have been calculated. Reruns of the model helped to find the most suitable starting year for the operation of a reprocessing plant with a capacity of 1,500 tons/a. In illustration 19 the results are shown. The following curves are plotted : the yield of irradiated heavy metal per annum (bottom), the accumulated heavy metal (top) and the installed capacity of the reprocessing plant (step curve). Besides the effect of reducing the amount of irradiated materials to be transferred to final deposits there is a saving or uranium imports of at least 30%.

IV. CURRENT RESEARCH

Energy modelling within the STE was begun with the aid of a DYNAMO compiler. Though being an appropriate tool for the macroeconomic module with its coupled differential equations, it is not the optimal instrument for the other modules. The energy supply module, for example comprises a set of simultaneous equations, some variables - for example capacities of power stations - even being discontinuous in time, as well as taking discrete values. Apart from that, for a large model the data handling within DYNAMO is not optimal, correlation analyses have to be made outside the model system, and a modular structure concept cannot be implemented.

In search of a new concept for integrating models, data (original and derived) and methods (e.g. regression analysis) we decided to apply FORTRAN using an interactive data- and method manipulation software package called RSYST III (4). Thus, having access to a large set of subroutine packages we also have the advantage of portability of programs from one computer to another. The data transfer between the modules, which now may be composed individually for each problem, is done by an interface program (described in more detail in (1)), RSYST III controlling background data manipulation with direct access in a timesharing environment.

With the aid of that concept we want to incorporate different optimization strategies, like those described in (8), for superposition to our models or modules with varying objectives and constraints.

BIBLIOGRAPHY

1. Niehaus, Friedrich. Computersimulation langfristiger Umweltbelastung durch Energieerzeugung: Kohlendioxid, Tritium und Radiokohlenstoff. Birkhäuser Verlag, Basel and Stuttgart, 1977 (in preparation).

2. Rath-Nagel, Stefan. Alternative Entwicklungsmöglichkeiten der Energiewirtschaft in der BRD - Untersuchung mit Hilfe eines Simulationsmodells. Birkhäuser Verlag, Basel and Stuttgart, 1977 (in preparation).

3. Reents, Heinrich. Die Entwicklung des sektoralen End- und Nutzenergiebedarfs in der Bundesrepublik Deutschland. Doctoral Thesis, University of Essen and Kernforschungsanlage Jülich, July 1977.

4. Rühle, R. "RSYST-I-III - Experience and Further Development". Atomkernenergie, Vol. 26 (1975), No. 3, pp. 185-189.

5. Schmitz, Kurt, et al. "A Model System for Analysing the Development of the Energy System in the Federal Republic of Germany". Proceedings, The IIASA Workshop on "Energy Strategies Conception and Embedding". International Institute for Applied Systems Research, Laxenburg, Austria, May 1977.

6. Schmitz, Kurt, et al. "Die Entwicklungsmöglichkeiten der Energiewirtschaft in der Bundesrepublik Deutschland - Untersuchung mit Hilfe eines dynamischen Simulationsmodells". Study, sponsored by the Stiftung Volkswagenwerk. Kernforschungsanlage Jülich, 1977. (Report in preparation).

7. Schöler, Ulrich, et al. "A Dynamic Energy Model for the Countries of the European Communities". Report for the European Communities, Brussels, June 1977. (Contract No. 048-76-EMD).

8. Schwefel, Hans-Paul. Numerische Optimierung von Computer-Modellen mittels der Evolutionsstrategie - Mit einer vergleichenden Einführung in die Hill-Climbing- und Zufallsstrategien. Birkhäuser Verlag, Basel and Stuttgart, 1977.

9. Voss, Alfred. Ansätze zur Gesamtanalyse des Systems Mensch - Energie - Umwelt - Eine dynamische Computersimulation. Birkhäuser Verlag, Basel and Stuttgart, 1977 (in preparation).