Working Paper

WAYS OF TRANSITION TO CLEAN ENERGY USE: TWO METHODOLOGICAL APPROACHES

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January 1987
WP-[/-15

International Institute for Applied Systems Analysis
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Foreword

The combustion of fossil fuels for the production of energy has already resulted in significant modifications of the earth's environment, primarily through the emissions of carbon dioxide, sulfur dioxide, nitrogen oxides, and particulates.

The modern world primary energy consumption patterns and its trends lead to the utilization of dirtier and more expensive fossil fuels. The desire to protect the environment is contradictory to such structural changes in energy like the broader use of coal as substitution for liquid fuels, taking into account the depletion of coal deposits with low sulfur contents.

Previous studies carried out at IIASA, in the FRG, the US, the USSR and other countries, formulate one long-term technological strategy that might limit pollutant emissions sufficiently to permit an efficient and ecologically sustainable development of the world's energy consumption patterns. This technological strategy is based on the implementation of the so-called Integrated Energy Systems (IES) or Integrated Energy-Chemical Systems (IECS). The basic idea of IES incorporates the decomposition and purification of primary fossil energy inputs before combustion, the integration of these decomposed (clean) products and the allocation of them in line with the requirements for final energy. Thus, Integrated Energy Systems represent a concept for providing a flexible range of final energy forms from varying inputs of different primary energy sources. Other potential advantages include improved performance of the whole energy system, such as higher efficiencies and lower environmental impacts.

The joint report of the Kernforschungsanlage Jülich (KFA), Jülich, FRG and the Siberian Energy Institute (SEI), Irkutsk, USSR describes the concepts, methodological approaches, and preliminary results of the analysis of technological options and technoeconomic properties of the different types of integrated energy systems. The study of KFA and SEI, based on the cooperation with the International Institute for Applied Systems Analysis, emphasizes the common viewpoint that the idea of integrated energy systems constitutes an essential basis for new studies on energy systems with a high degree of utilizing primary energy sources and with low emissions.

Vassili Okorokov
Leader
Integrated Energy Systems

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by

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1. Introduction - The Energy Problem

During the last decade, political and scientific discussions were dominated by the energy problem. The oil price shocks in the 1970's had focussed public attention to the question whether there was still sufficient energy in the world to satisfy a growing demand. Many scientists have dedicated their work to this question and many reports have been written. All these studies came to the same conclusion: There is no quantitative restriction on energy in the world. However, it is debatable how to use this energy in a responsible manner, particularly with respect to nature.

In the long run, there are sufficient hydrocarbon resources on earth to sustain supply. Their quality, however, will be decreasing and it will be increasingly difficult and costly to make them accessible and to utilize them. As an example, the crude oil liftings will become heavier in the long run (Orinoco type of crudes, tar sands) with, at the same time, increasing concentrations of hetero atoms, like sulphur, nitrogen or heavy metal compounds. Structural changes, like a broader utilization of steam coal substituting for gas and liquid products, will create additional environmental problems. This concerns handling as well as converting "dirty energy".

On the other hand, nature does not provide an unlimited reservoir for the deposition of wastes. Therefore, the energy problem has to be restated under a different viewpoint. The open question now is rather how to use "energy in a finite environment", than how to use it with finite resources.

The research objective is to develop new technological concepts for a cleaner energy future. Historically abatement measures have been a first step in the evolution of an effective energy waste management. Increasing restrictions on emissions will, however, sooner or later lead to a point where the cost of abatement measure will start increasing exponentially. Figure 1 demonstrates this effect for a flue gas desulphurization (FGD) unit of a coal fired power plant. (The cost of stack gas cleaning is plotted as a function of SO_2 removal). The need for alternativ, economically mor viable options is apparent.

The solution of complex technological problems very often requires visions of technical options never considered before. In the context of a clean energy supply, such a vision was formulated by Wolf Häfele in the early 1980's which he termed the concept of a "Novel Horizontal Integrated Energy System (NHIES). Figure 2 drafts the idea of NHIES, comparing it with the classical energy systems.

Analyzing the structure of the present energy supply, it is apparent that there is horizontal competition between the traditional energy sectors (coal, gas, oil, nuclear). However, vertically, on the way from the primary resource down to final consumption, there is virtually no interdependence between energy sectors. Every energy sector is equipped with its own supply, processing, distribution, - and waste management.

The basic idea of novel energy systems now incorporates the integration of the traditional vertical structures. This integration can be realized at different levels. The highest degree of integration would be reached when all energy carriers are decomposed into their elementary components. The consumer is supplied with just those elements he requires. Unwanted components, like hetero compounds, are removed at conversion level.

Integrated systems link the optional energy resources already at a very early stage of processing. Supply disruptions in one primary resource can then be easily compensated by simply switching to other resources. The infrastructure would not be affected and the consumer would not even notice. The risk of supply is levelled down by a highly resiliant system.

Last, but not least, the integrated system provides the possibility of a highly effective utilization of resources.

2. Research Objectives and Premises

Both the Jülich Nuclear Research Center (KFA) and the Siberian Energy Institute (SEI) have initiated research on the opportunities of novel integrated energy systems and their competitiveness against conventional energy systems. Primary research objective is to identify combinations of new technological options which can contribute to an environmentally clean and highly efficient energy supply. Most of these options are not economic yet. Their competitive position may, however, improve with increasing environmental restrictions.

It is clear that in two countries as different as the USSR and the Federal Republic of Germany the premises of research on integrated energy systems are quite different as well. The USSR differs from the FRG in territory, population density, energy consumption, environmental conditions as well as in the availability of national energy resources and their regional distribution.

The analysis of integrated energy systems in the USSR is therefore very closely related to the development of regional energy supply concepts. This is particularly valid when the utilization of low-grade but rather cheap energy resources (like the Kansk-Achinsk coals) is considered in highly industrialized areas. As district heating has a share of more than 50 % in the present USSR energy supply, combined power and heat production will constitute an important element of potential integrated energy system concepts. The geographical distribution of indigenous energy resources in the USSR adds the "transportability" of energy carriers as another relevant criterion in selecting the right configurations of integrated energy systems.

The research in the Jülich Nuclear Research Center is more directed towards the study of the opportunities of a highly integrated energy system (NHIES) as an alternative or complement to the traditional energy supply in the FRG. An optimum system configuration has to be selected among all technical options that provides clean energy at a high degree of resilience against supply disruptions and guarantees an effective usage of resources. At the same time, the competitiveness of such a system has to be judged by measuring and quantifying the reactions of the existing energy system on stronger environmental restrictions.

In the following sections, the analyses of integrated energy systems carried out at KFA and SEI are described in more detail. It is evident that different research premises, as outlined above, imply different methodological approaches. There is, however, the common research objective to investigate novel technological options and to provide a scientific basis of conceptually describing, analyzing and finally understanding "energy in a finite environment".

3. The KFA-Research on Integrated Energy Systems

3.1 Concepts and Methodological Approach

Research objective at KFA has been to investigate the opportunities of a highly integrated energy system (NHIES) in competition with the traditional vertical structures of the existing energy supply. The novel system is realized by decomposing energy carriers into their elementary components in a set of so called NHIES-technologies. Basic NHIES technologies are nuclear gasification producing synthesis gas from coal, (natural) gas separation, a molten iron process for coal gasification, electrolysis, CO-turbines and a methanol plant. The selected set of technologies produces methanol, electricity and gas by converting the whole spectrum of primary energy carriers. The economics of the NHIES are determined in competition with the existing energy supply system to which conventional abatement measures are added to reduce pollution.

The primary task now consists in quantifying the competitive position of the NHIES-concept compared with the conventional energy system when environmental constraints are parametrized towards "zero emission standards" - i.e. very restrictive emission constraints.

In practice, this means to consistently compare a great number of technologies, considering their technological parameters as well as their economics. Linear programming (LP) is a well established instrument for doing this on an operational basis. The theory of LP is so well known, that there is no need for further theoretical detail in this article. An LP-model called MARNES was developed which is solved by minimizing the total system cost of energy supply and consumption.

3.2 The LP-Model MARNES

The MARNES model consists of a NHIES module and a module representing the conventional energy system. NHIES is a combination of about 70 technologies. The conventional part is described by

an electricity sector:	power stations based on nuclear, coal, oil, gas; electricity transportation and distribution grid, electricity consumers (domestic, industrial, train, traffic) + abatement measures
a refinery sector:	average german refinery plus product desulphurisation, oil product consumers (domestic, industrial, traffic) + abatement measures
a gas sector:	transportation and distribution grid + storage effects, gas consumers (domestic, industrial) + abatement measures
a coal sector:	distribution and coal consumers (industrial, domestic) + abatement measures

About 150 technologies are modelled to define these sectors. In LP-terms, every technology can be described as a black box which is characterized by the following parameters

input streams:	energy and/or mass streams
output streams:	energy and/or mass streams
cost parameters:	capital cost + fixed charges (insurance, tax, etc.)
	variable cost (operational cost)

The technologies - or boxes - are linked via mass or energy streams. The result is an energy and mass flow model, starting with the primary resources (coal, oil, gas etc.) and ending with the final consumption of useful energy (km driven in a car, space heat for houses, etc.). Figure 3 illustrates the principal set up of the model. Every step from the primary resource to the end-user (conversion, distribution, consumption) is characterized by its specific cost - and often also by side-streams to the environment (emissions, depositions). All costs are accounted for in the objective function of the model and are minimized to find an optimum system configuration. The side-streams (like SO_2, NO_x or CO_2 emissions) are controlled in balance inequalities with exogenously given upper limits. In order to meet these limits, the model can choose between abatement measures in the conventional system or the construction of NHIES-technologies.

In the LP-model energy conversion and consumption are triggered by an exogenously given demand scenario which is calculated by a simulation model from exogenous parameters like GNP-growth rate, energy prices, specific energy consumption etc. The dynamic LP-model is segmented into 8 periods giving rise to a time horizon of 50 years.

3.3 Preliminary Results

The modelling activities are now in the final stage. They are documented in preliminary reports /1-5/. A set of computer runs has been carried out with the model.

Some results of computations are discussed below in order to illustrate the model structure.

In the following we will discuss a scenario (as shown in Table 1) with moderate parameters and demand assumptions over time. The time horizon for the optimization is the period from 1980 to 2030.

In addition to the scenario assumptions, bounds were set on the mining of hard coal (lower bound) and lignite (upper and lower bound) to reflect the status of national coal contracts and governmental policy. Parallel to the bounds on primary energy, additional constraints were set on useful energy consumption to simulate the influence of other parameters apart from costs on the behaviour of the end-users. For example, although coal is relativly cheap for space heating, most people avoid coal-heating because of its uncomfortable handling.

Important constraints in the model are the limits on SO_2- and NO_x-emissions given as upper bounds. In the computations the dynamics of these bounds were varied widely in order to give rise to different "cases", for example a rapid or a slow decrease of SO_2 over time.

From the avaibable set of cases, one case (case 5) is analysed in this article comparing it with a base case.

Scenario

Basic assumptions:
- GNP Growthrate ca. 2 %/a
- Energy prices constant
- Useful heat for space heating ca. constant
- Specific energy consumption decreasing

Demand

Sector / Year	1980	1985	1990	1995	2000	2010	2020	2030
Driving performance cars (10^9 km/a)	309	349	379	390	395	392	392	392
Freightage trucks (10^9 tkm/a)	126	129	141	153	165	182	182	182
Process heat (TWh/a)	326	300	313	321	329	341	327	312
Space heating (TWh/a)	618	570	587	593	598	594	597	600

Table 1: Scenario assumptions

- The base case includes the current emission standards for large vessels in utilities and industries GFAVO (= Großfeuerungsanlagenverordnung) as well as legal regulations for NO_x-reduction in the transportation sector (e.g. catalyst cars).
  The results of the base case are represented as dotted lines in the figures.

- In case 5, restrictive bounds were set on the SO_2- and NO_x-emissions, supplementing the constraints of the base case in order to initialize NHIES.

Figure 4 shows the required emissions for NO_x (upper graph) and SO_2 (lower graph) as a function of time.

In order to meet these emission standards, the model first reduces emissions in the sector conversion + industry using conventional denoxation and desulphurization, which are the cheapest options for an additional reduction of NO_x- and SO_2-emissions. When stack gases are totally clean, structural changes in the residence + transportation sector occur to achieve a further reduction of emissions. This takes place in the period after the year 2000 by increasing methanol and electricity consumption in order to meet emission standards. This yields a sharp increase in the NHIES-activity after 2000, when hard coal, natural gas and nuclear energy are used to produce synthesis gas (Figure 5).

The contribution of NHIES to the final energy demand is shown in more detail in Figure 6. The maximum methanol production covers a portion of ca. 30 % of total final energy. Methanol is used for heating and for transportation. In addition to methanol, SNG (synthetic natural gas) is produced in NHIES. The SNG is injected into the national natural gas transportation grid. Some of the primary energy in NHIES is also converted to peak load (CO-turbine) and base load (HTR cogeneration) electricity.

The substitution of final energy carriers for transportation and heating is illustrated in Figures 7 and 8. The dotted lines represent the base case.

Due to strong NO_x restrictions, methanol substitutes for gasoline and diesel. In 2030 methanol covers nearly 100 % of traffic fuel implying a reduction of NO_x-emission by a factor of 10 in the transportation sector compared to 1980.

Gas oil for space heating is additionally substituted by methanol, which later on is replaced again by electricity. The production of electricity therefore strongly increases in the last decade.

The structural change in primary energy, as a result of the substitution process discussed above, is shown in Figure 9. In the base case as well as in case 5 the share of nuclear energy increases, substituting parts of the hard coal. In case 5 oil nearly disappears. Its share is covered by nuclear energy and natural gas (which is also input to NHIES).

Figure 10 shows the annual total system cost on a 1980 price basis. These costs are composed of operating expenses and investments. Whereas the operating expenses stay relatively constant in all computed cases, the annual investments increase with 30 % in case 5 compared to the case with no emission restrictions. Additional cost for the reduction of emissions cover a share of only 10 % of the total system cost of appr. 270 billion DM/a in the year 2030.

4. The SEI-Research on Integrated Energy Systems

4.1 Concepts and Methodological Approach

SEI's approach in the analysis of integrated energy systems is determined by the particularities of the USSR energy development as described in Chapter 2. Basic considerations are:

- Novel integrated energy systems in the USSR will be, as a rule, local systems with different structures in different regions of the country. The structures will mainly be determined by the availability of primary energy resources in the respective areas. In the Kansk-Achinsk region, for example, major objective in the development of an energy system will be the effective utilization of the available coal.

- Novel systems in the USSR are planned to be realized stage-by-stage making use of new, not fully developed technologies. This requires to focus special attention on the long-term forecasting of future technological development (improvement and introduction of new technologies). This includes the evaluation of potential technical and economic parameters of new technologies.

- Energy transportation is of great importance in the USSR. Therefore, efforts should be aimed at obtaining more "transportable" energy carriers at higher energy densities.

- As district already has an important share in todays USSR energy supply, integrated energy systems will comprise subsystems of district heating, including cogeneration.

A general schedule of the SEI research on novel integrated energy systems is outlined in Fig. 11. This schedule has been followed in the investigation of an integrated system for the Kansk-Achinsk region.

The study of the long-term energy complex development (block 1) determines composition und volumes of primary energy resources available to integrated energy systems in different areas of the country and quantifies the demand for products as synfuel, electricity and heat.

The task of forecasting the development of new technologies (block 2) generally precedes detail studies of integrated systems although an iterative adjustment may be required. At this stage, this activity plays the most dominant role in SEI's research. Two types of models (MOPR and MOST) are used for this purpose.

The results of the technology forecasts form the basis for the **preliminary selection of technologies and the analysis of the potential variants of energy transportation** (block 3 in Fig. 11) taking into account of the data, obtained from the energy complex analysis (from block 1). In this way, a wide set of candidate technologies is generated and potential means of energy transportation are selected for the study of integrated energy systems in each area.

Then **the structure of the integrated system is optimized in a systems model called MOST** (block 4). The MOST model is a linear optimization model similar to the MARNES model which minimizes the total cost (investments and operational expenses) of the integrated energy systems.

Purpose and nature of the research activities represented in blocks 5 and 6 of Fig. 11 are evident.

Thus, the methodology for studies on novel integrated energy systems developed in SEI, comprises three types of mathematical models: a systems model (MOST), technological unit models (MOTUS) and physico-chemical process models (MOPR).

4.2 Preliminary Results

The SEI research on novel integrated energy systems is at this stage mainly concerned with the long-term forecasting of technological development (see block 2, Fig. 11).

In order to establish a quantitive basis for the selection of technologies that can potentially be used in integrated energy systems, **a physico-technical classification of technologies** is advisable. One variant of such classification, proposed by SEI for coal processing and combustion, is given in Fig. 12.

A next stage in forecasting technological development now consists in the **evaluation of the technologies' maximum (theoretical) energy indices** (specific fuel consumption b and efficiency η). This estimate is needed for a preliminary comparison of new technologies, judging the potential of their improvement. The evalutation is realised by calculating the thermal effects of the main chemical reactions at thermodynamic equilibrium. Thermo-chemical processes models (MOPR) have been developed for this purpose.

Tentative estimates of the theoretically achievable technical parameters of coal processing and energy transportation are summarized in Tables 2 and 3 respectively. The potential for a reduction of the specific fuel consumption b and an increase of the efficiency η in coal processing (Table 2) are

Table 2

Tentative indices for coal processing technologies

Final product	Technology	Current indices		Theoretically achievable indices		
		η_t,%	b	η_t,%	η_t^c,%	b
SNG	Hydrogasification	65 - 78	1.28	81.4	-	1.19
	Hydrogasification + NPH			85.1	85.7	1.01
	Gasification + synthesis	55 - 68	1.47	68.0	75.4	1.38
	Gasification + NPH + synthesis			71.6	77.1	1.01
SLF	Hydrogenation	64 - 72	1.39	91.8	-	1.09
	Hydrogenation + NPH			92.4	-	1.08
	Gasification + NPH + synthesis			73.2	80.2	1.00
	Gasification + synthesis	35 - 42	2.38	69.6	76.9	1.35
	Gasification + methanol synthesis + Mobil process	43 - 48	2.08	69.6	76.9	1.35
	Gasification + NPH + methanol synthesis + Mobil process			72.3	80.2	1.00
Methanol	Gasification + synthesis	49.51	1.96	76.8	83.7	1.23
	Gasfication + NPH + synthesis			80.8	85.4	0.90
Hydrogen	Gasification + conversion	55.60	1.67	81.6	-	1.23
	Gasification + NPH + conversion			85.7	-	0.84
Semicoke, tars	Pyrolsis	76	1.32	95	-	-

Notes: η_t - thermal efficiency of coal processing
η_t^c - the same with the combined electricity production
b - specific coal consumption (coal (t.c.e.)/final products (t.c.e.));
SNG - substitute natural gas
NPH - nuclear power heat
SLF - synthetic liquid fuel

Table 3

Evaluation of theoretically achievable comparative indices for energy carrier transport

Energy carrier	Relative heating value H_i/H_o	Relative capacity of a pipe- C_i/C_o	Efficiency of pipeline transport η_i (%)	Relative expenditures on the pipeline transport[+] E_i, n=var	E_i, n=1	Index i
Water $\Delta t = 80\ ^oC$, $t_{av} = 100\ ^oC$	1	1	93.8	1	1	0
Water $\Delta t = 150\ ^oC$, $t_{av} = 150\ ^oC$	1.79	1.83	96.5	0.55	0.78	1
Synthesis gas $(CO + 3H_2)$[++] P_{av} = 6Mpa	0.0066	2.57	80.40 (84.40)	0.61 (0.39)	1.1 (0.68)	2
Hydrogen (H_2), P_{av}=6Mpa	0.0336	27.0	96.90	0.037	0.27	3
Methane (CH_4) P_{av} =6Mpa	0.112	31.8	99.10	0.031	0.25	4
Motorfuel (CH_2)	109.4	119.7	99.94	0.0084	0.15	5
Methanol (CH_3OH)	52.2	57.4	99.88	0.017	0.20	6
Slurry $(C+H_2O)$ $(C/H_2O$ =0.5)	62.3	53.28	99.90	0.019	0.20	7
Slurry $C+CH_3OH)$ $(C/CH_3OH$=0.6)	101.8	90.2	99.94	0.011	0.16	8

\+ n- the number of pipes in the line

++ - indices in brackets are given without expenditures on the methanation product return to the heat source evaluated taking into account the utilization of exogenous heat from exothermal processes and the physical heat of products.

Comparative indices for energy carrier transportation (Table 3) are generated solving hydrodynamic equations with the technique described in /1/. Hot water with an average temperature of 100 ^{o}C during transportation and cooled by 80 ^{o}C at the consumers is taken as a reference energy carrier. Expenditures, required to pump water back to the heat source are neglected. The efficiency of synthesis gas transportation is evaluated on the assumption that it is methanated (not burnt) in the consumption installations. All transport efficiencies (η) are determined for a transportation distance of 1000 km and pressure losses of 20 MPa.

The data presented in the tables give certain idea on the development trends and the potential of technological improvement, that in turn facilitates the selection of a set of candidate technologies for integrated energy systems. Table 2 illustrates the high energy efficiency which is achieved when coal processing is combined with nuclear heat production. It also illustrates the expediency of combined coal processing and electricity and heat generation.

The transportation parameters given in Table 3 indicate an interesting relation between the comparative transport efficiency and the volume of transported energy (columns $\dot{E}$ with n=var and n=1). In a large-scale transportion system, where an increase in the pipeline capacity requires additional pipelines (n=var), the differences in the transportation efficiency for different energy carriers are much more significant than in small-scale transportation systems, where the increase in pipeline capacity is achieved by larger pipeline diameters (n=1).

The evaluation of the technical and economic characteristics (see section in block 2, Fig. 11) constitutes an important stage in technology forecasting. The practically achievable technical and economic indices, and in particular the specific capital investments for technologies, that are at an early stage of development and have not been demonstrated in prototypes, are of great uncertainty. To nevertheless determine these indices in the required way (for the most important technologies), special models (models of the technological unit - MOTUS) have to be developed. In these models, material flows, energy flows and thermodynamic parameters of the unit components are optimized for a given technological structure. The cost of each single element is evaluated analysing the analogy with the design and physical parameters (heat-exchange area, vessel volumes, pressure, etc.) of existing equipment. For the calculation of the physico-chemical process parameters in MOTUS, the MOPR models are applied.

Along with the formulation of the methodical principles and evaluation of potential process indices, SEI obtained first results in the structural analysis of integrated energy systems and in the detail characterization of particular technologies.

Computer runs made with the MOST model indicate a strong dependence of the potential structure of integrated energy systems upon the future energy complex development in the country as a whole and in each individual region. As an example the economic effectiveness of direct hydrogenation technologies increases with increasing synthetic liquid fuel demand, whilst the opportunities of the pyrolysis technology improve with the increase in the volume of Kansk-Achinsk coal extraction, etc.

The results of an assessment carried out for coal combustion in a catalytic fluidized bed (catalytic heat generator-CHG) /7, 8/ is of interest. The main advantages of CHG boilers over an inert fluidized bed are:

- an entire elimination of sulphur oxide and carbon monoxide emissions and a considerable reduction of nitrogen oxide emissions;
- the possibility of dividing the fluidized bed into several non-isothermal zones. This will decrease the temperature in the upper zone to 120-150 ^{o}C. That in turn allows the reduction of the total fluidized bed heating surface.

Some results of a CHG efficiency evaluation are presented in Fig. 13. The uitilization of a catalytic heat generator in heating plants gives the highest environmental and economic effect. Probably, the CHG can also be efficiently used in coal pyrolysis and in electric power plants.

More detailed results of SEI's assessments of new coal processing technologies, in particular tentative estimates of the plasma gasification process are given in /6/.

5. Conclusions

Studies of the Siberian Energy Institute, Irkutsk, and the Nuclear Research Center, Jülich, carried out with the aid of complex computer models, demonstrate the opportunities of novel integrated energy systems in a future, clean energy supply. As conditions differ widely in different regions and different countries, there will of course be a wide structural variety in the realization of integrated energy systems. The studies of SEI and KFA, based on the cooperation with the International Institute of Applied Systems Analysis (IIASA), emphasize the common viewpoint that the idea of integrated energy systems constitutes an essential basis for future studies on "energy in a finite environment".

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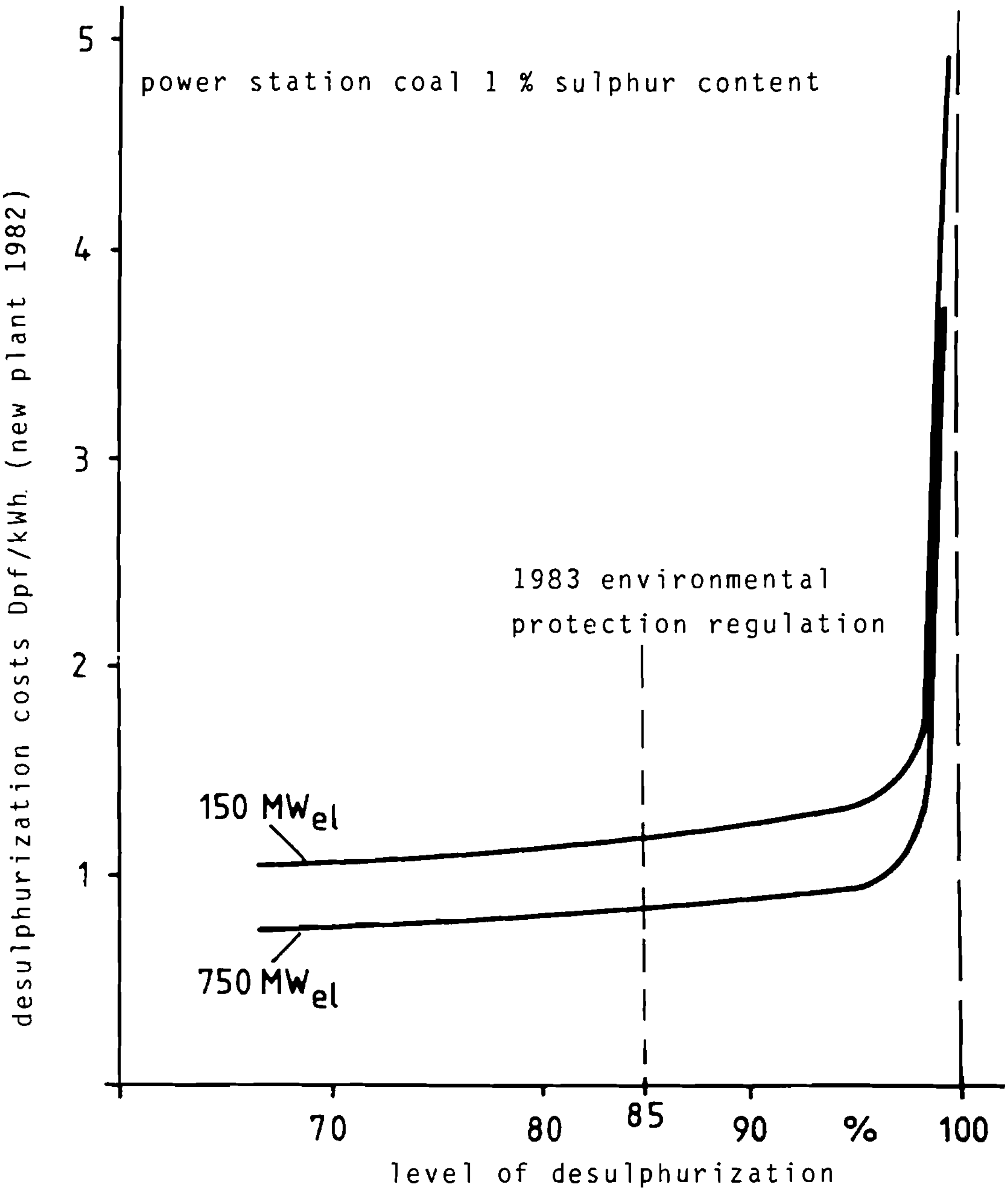


Fig. 1: Cost Picture of Wet Processes with Marketable Gypsum Production for German Power Stations. Tolerance ± 15 %, Turnkey Facility + 25 %.

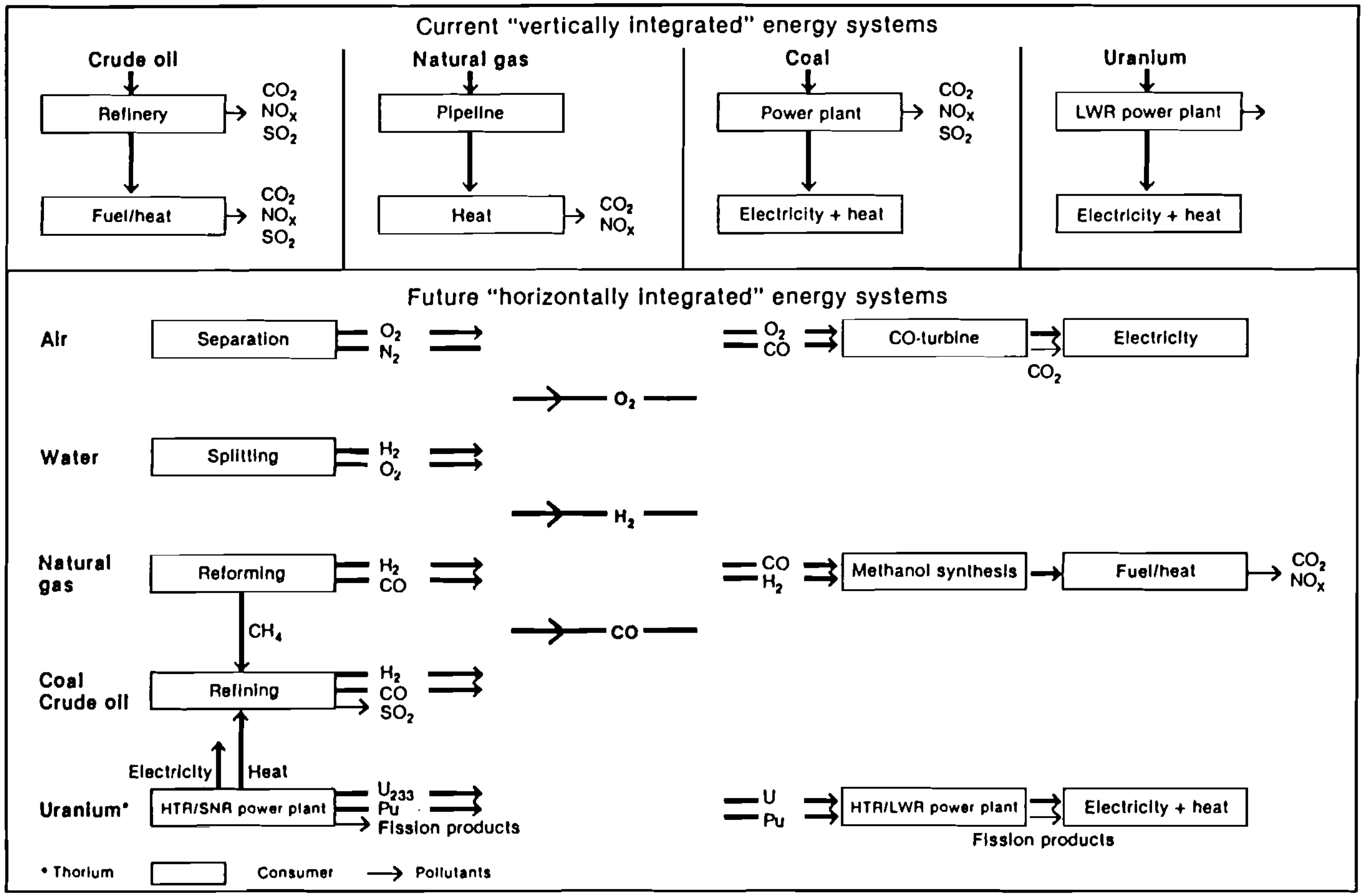


Fig. 2: Concept of integrated energy systems

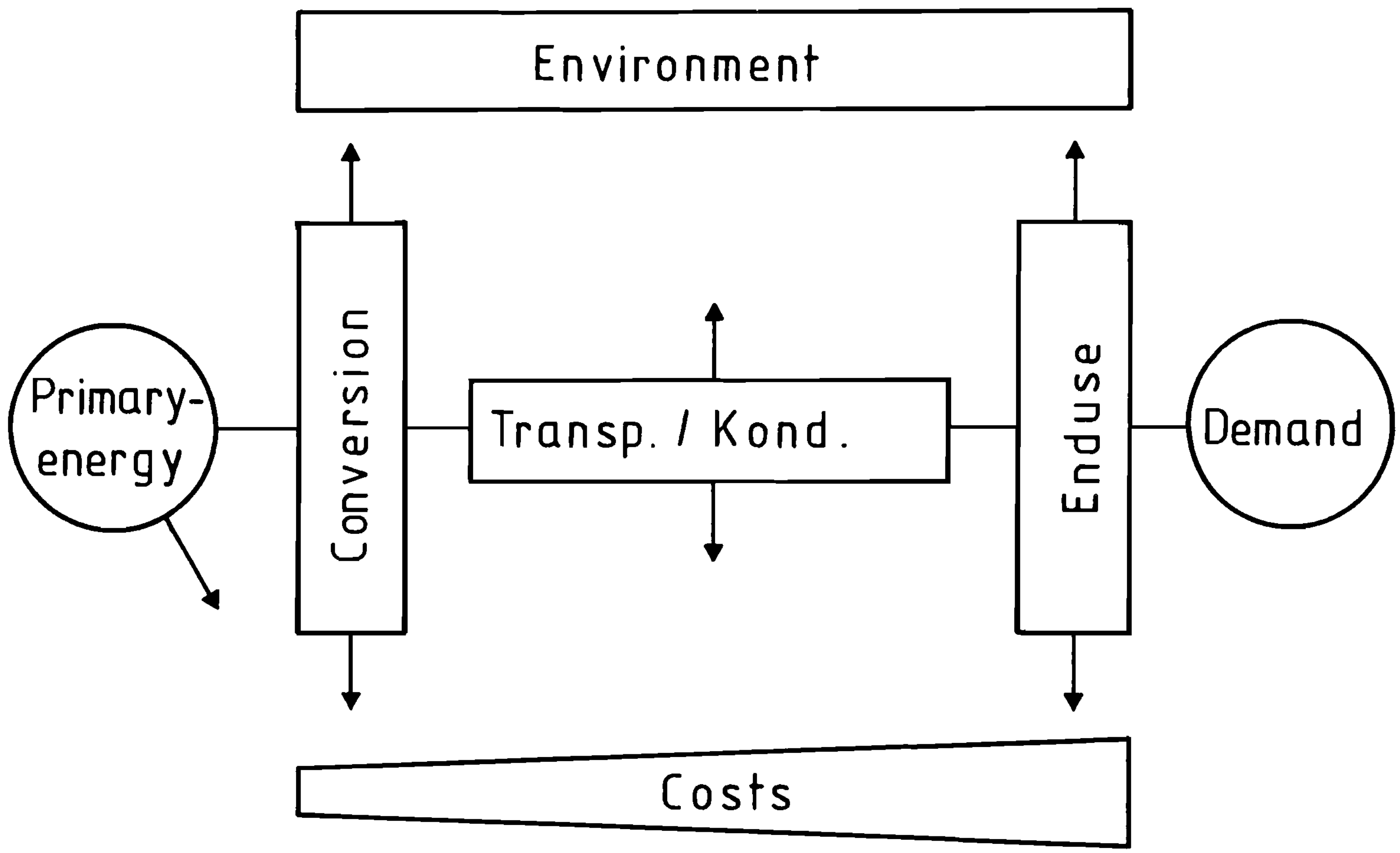
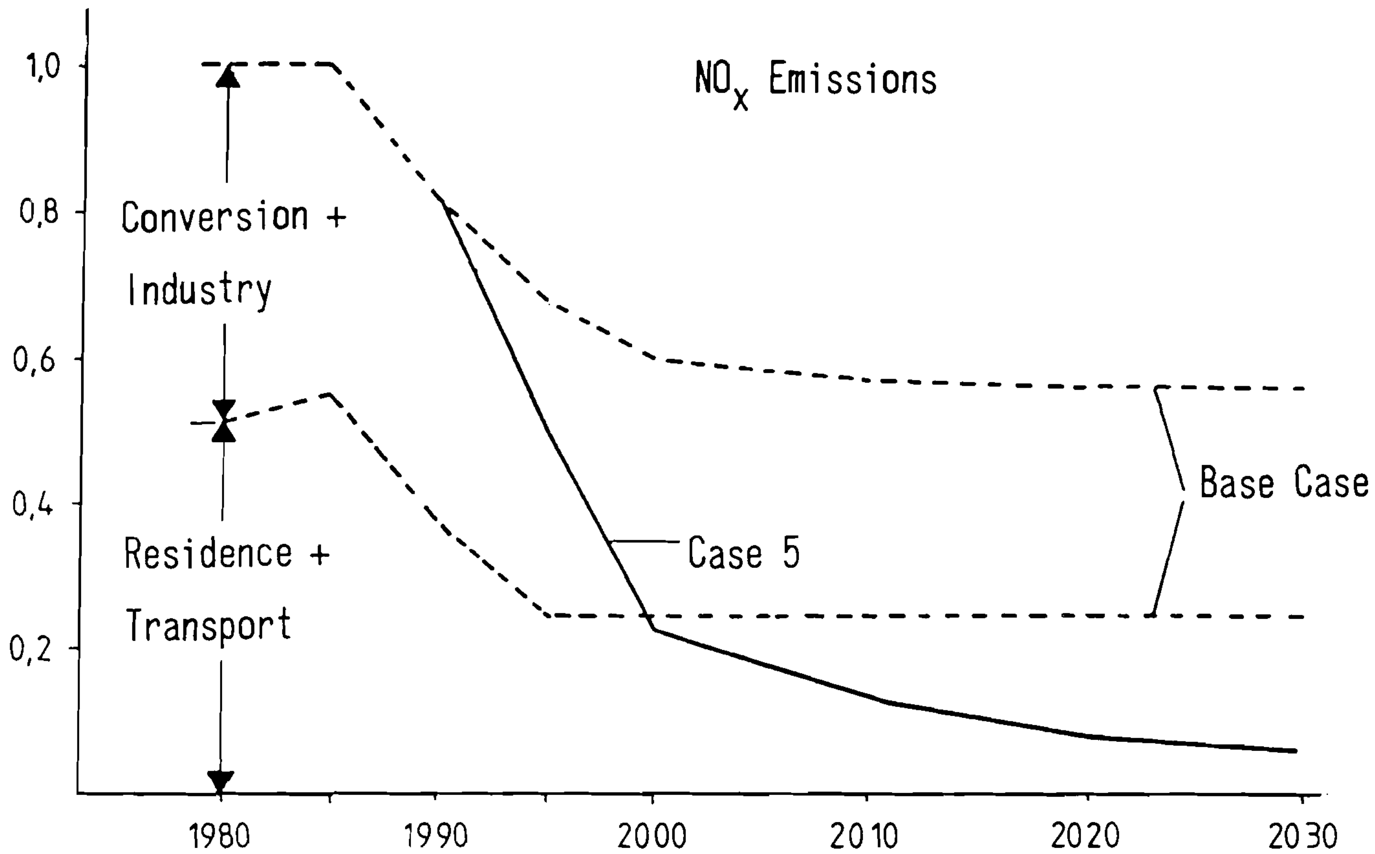


Fig. 3: Principal model structure



Base with GFAVO and catalyst cars from 1990

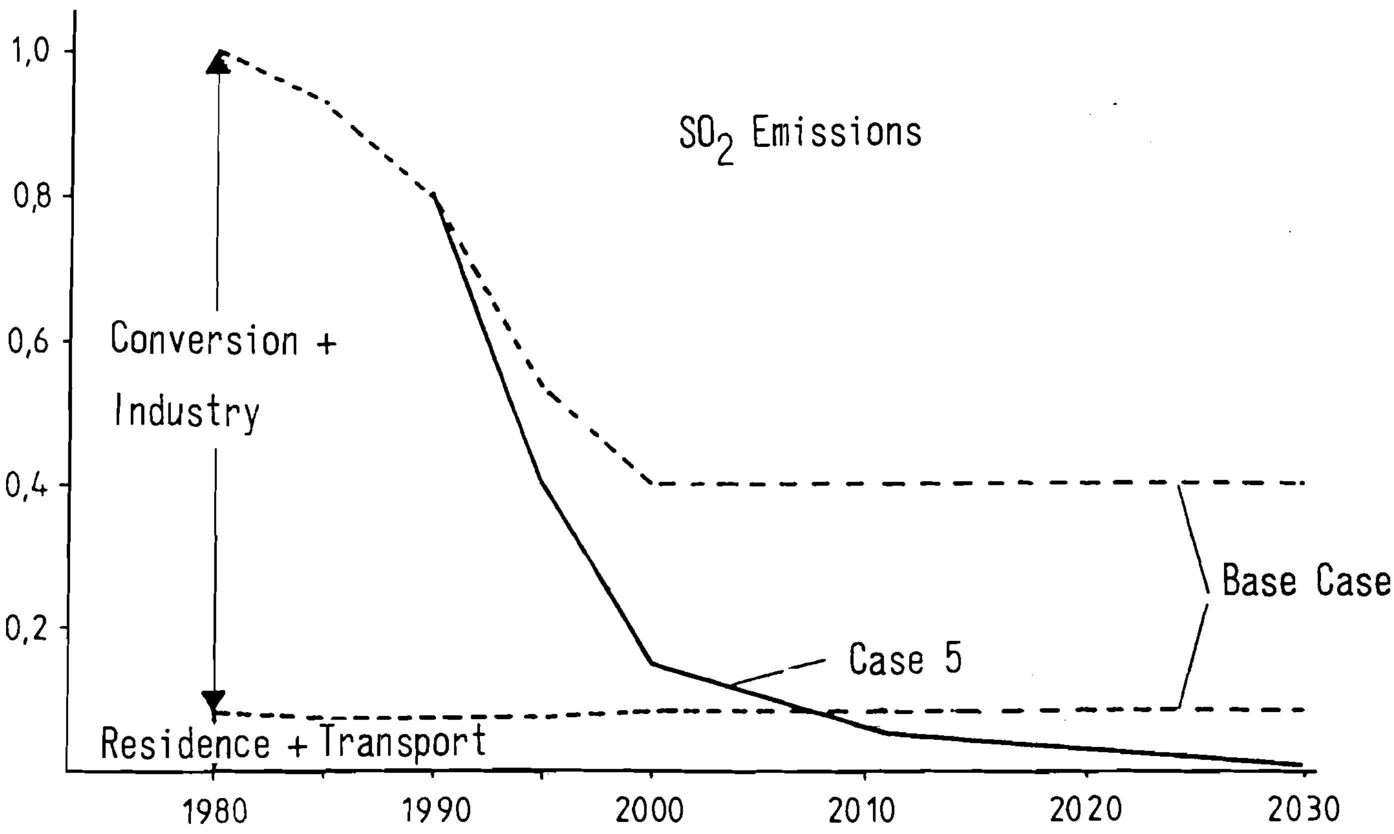


Fig. 4: NO_x and SO_2 Emissions

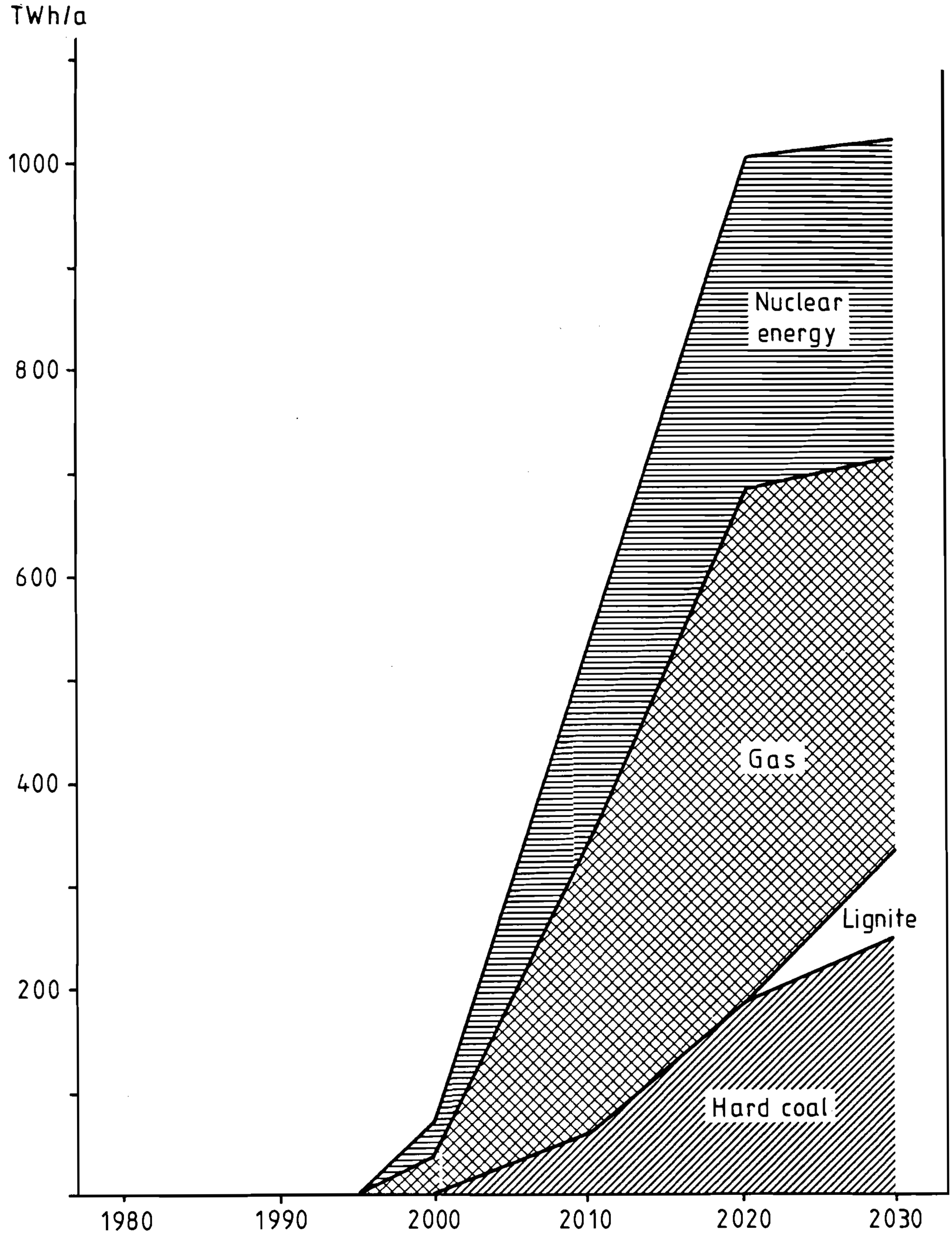


Fig. 5: Case 5: Primary energy for the Novel Horizontally Integrated Energy System

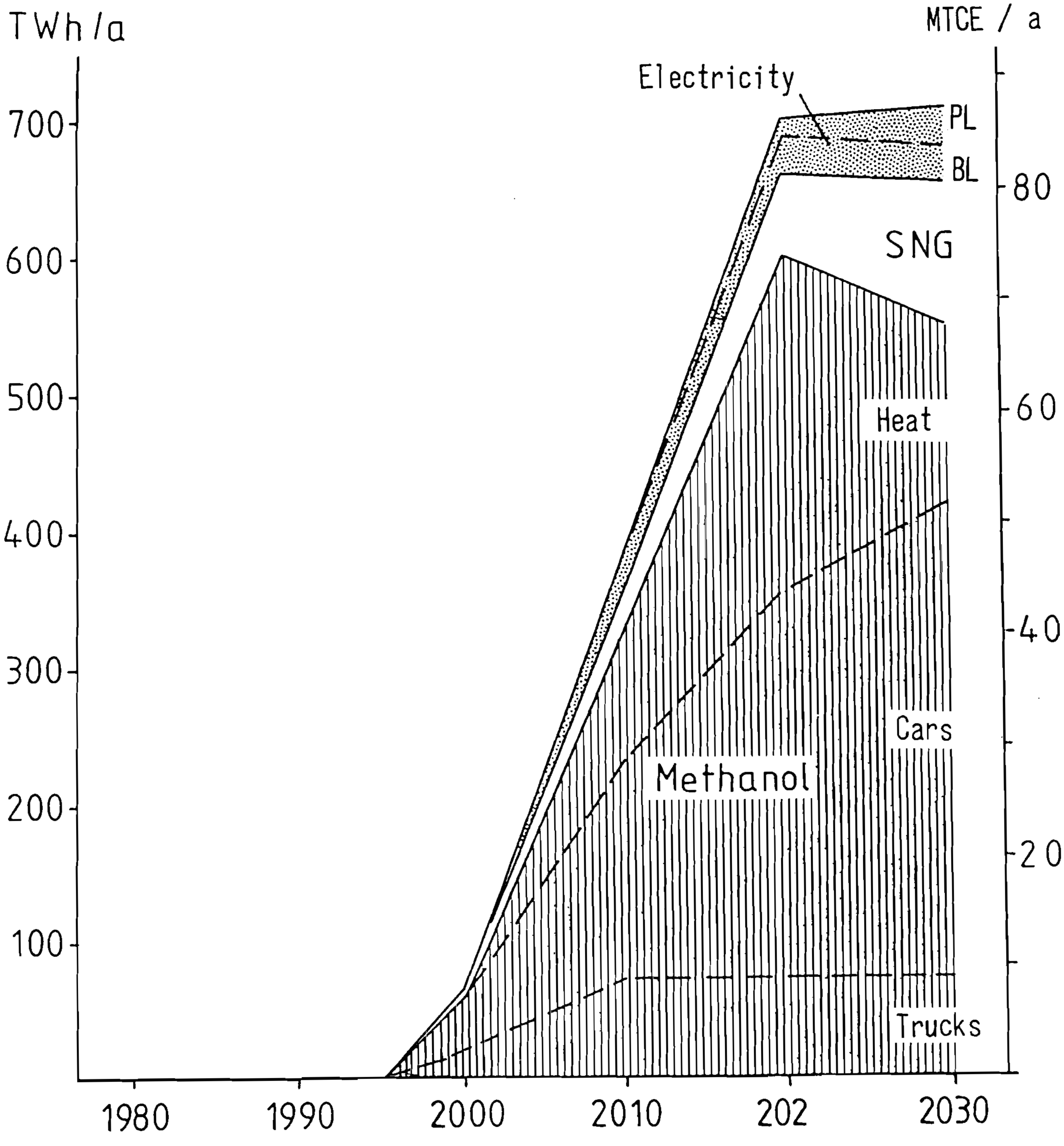
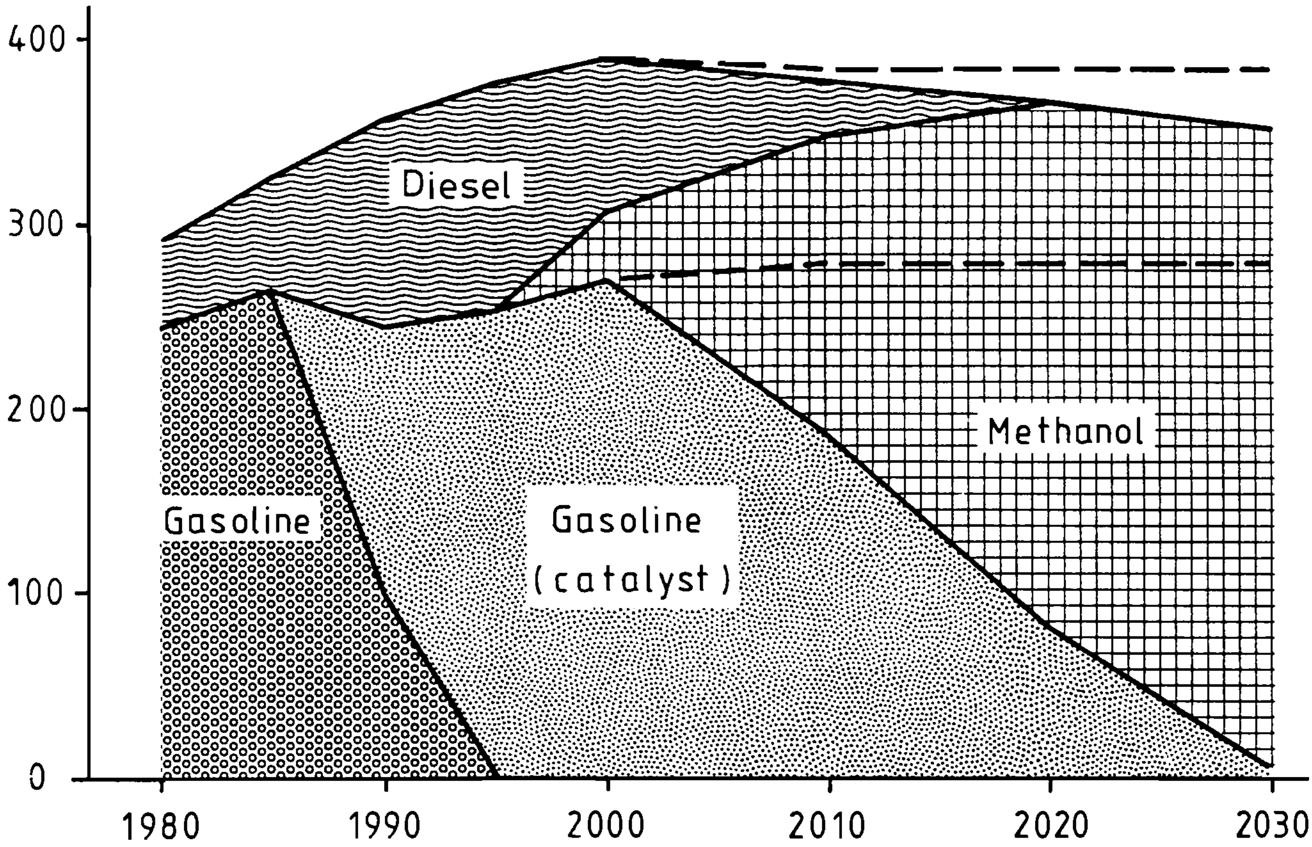
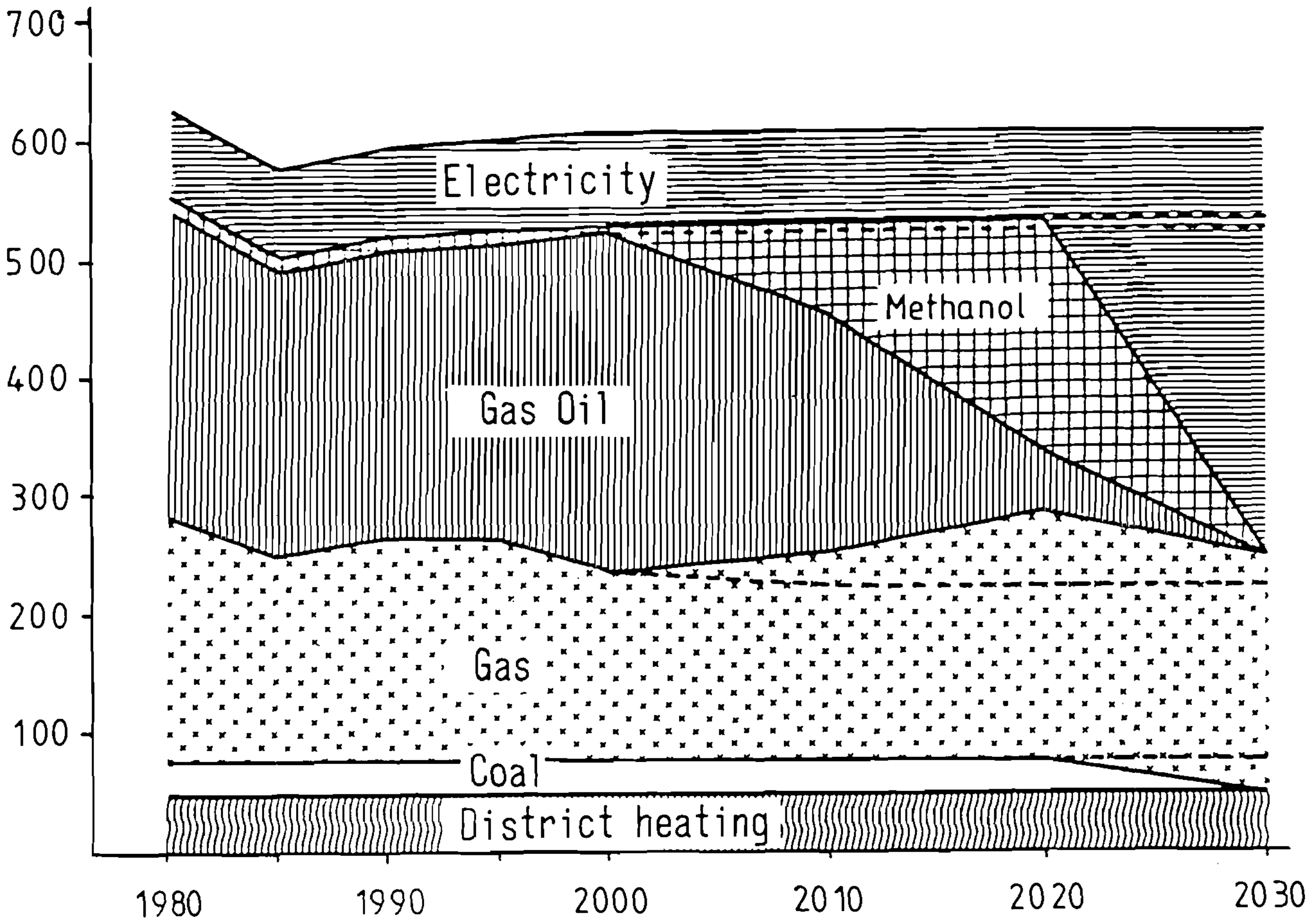


Fig. 6: Case 5: Final energy from NHIES



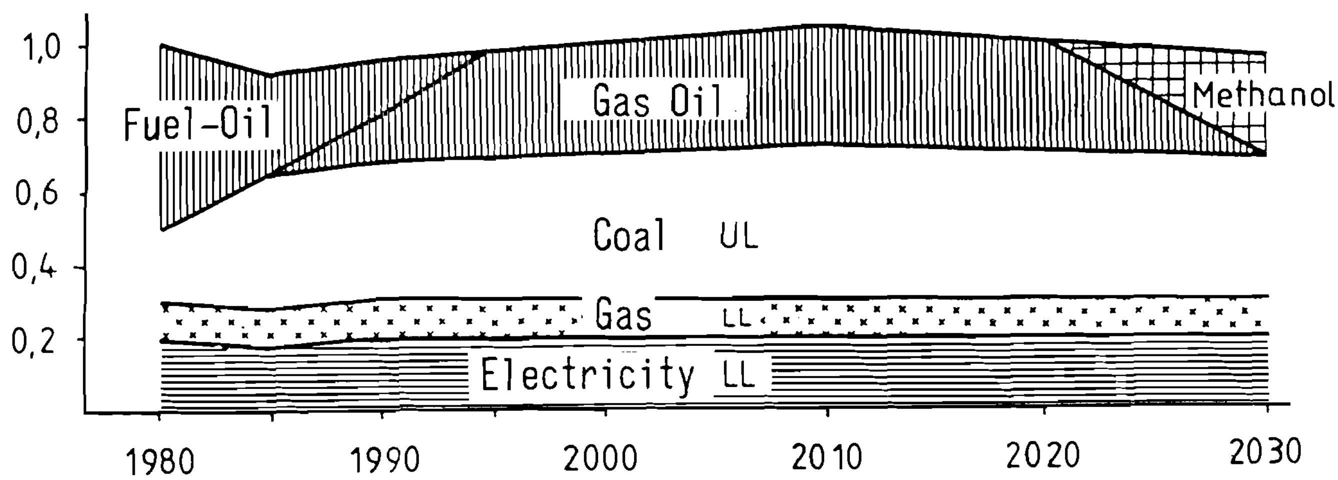
(– – – = Base Case)

Fig. 7: Case 5: Fuel for cars (TWh/a)



(- - - = Base Case)

Case 5: Useful energy for space heating (TWh/a)



Case 5: Process heat, 1 = 326 TWh/a

Fig. 8: Useful energy for heat production

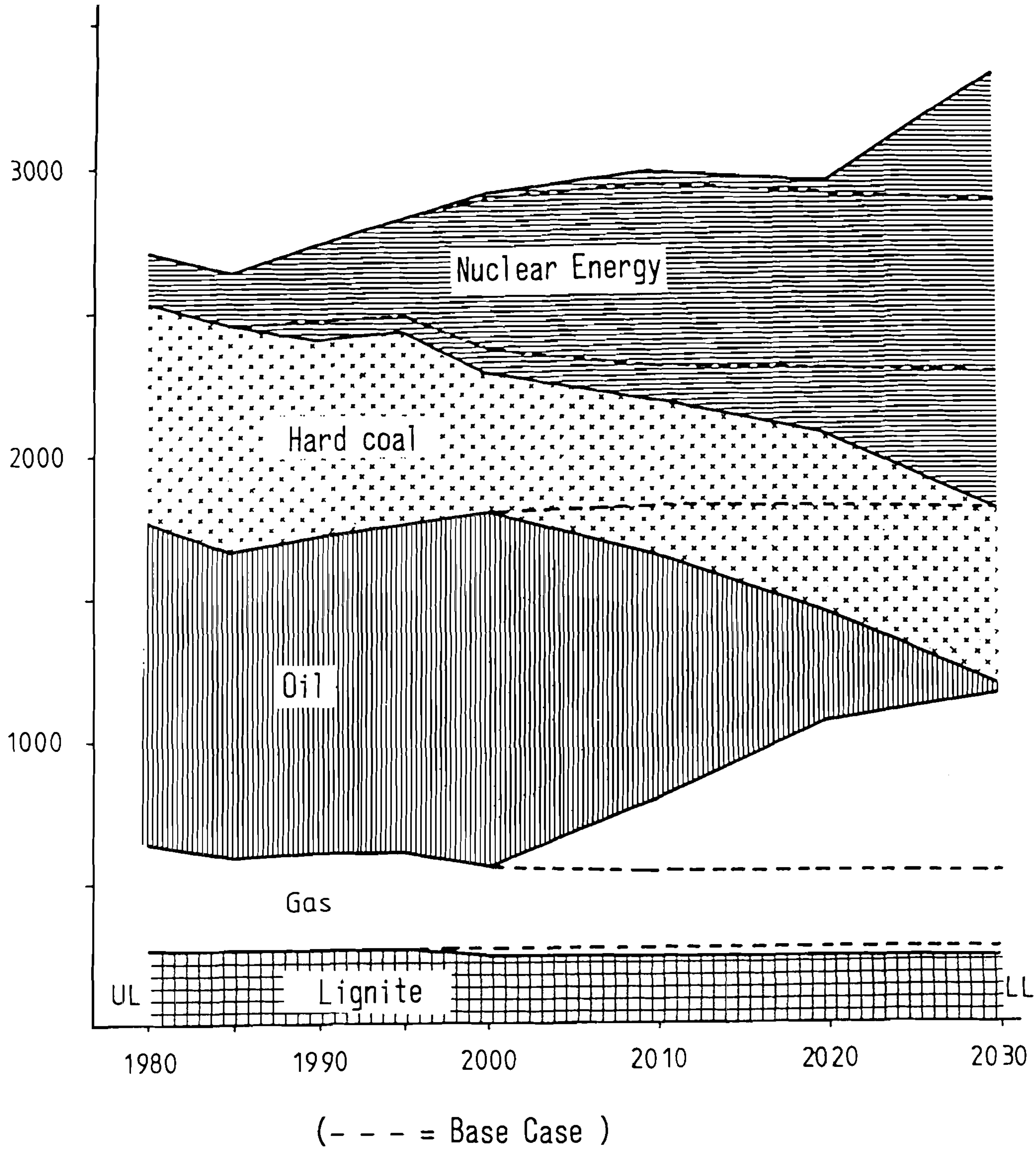


Fig. 9: Case 5: Total Primary energy (TWh/a)

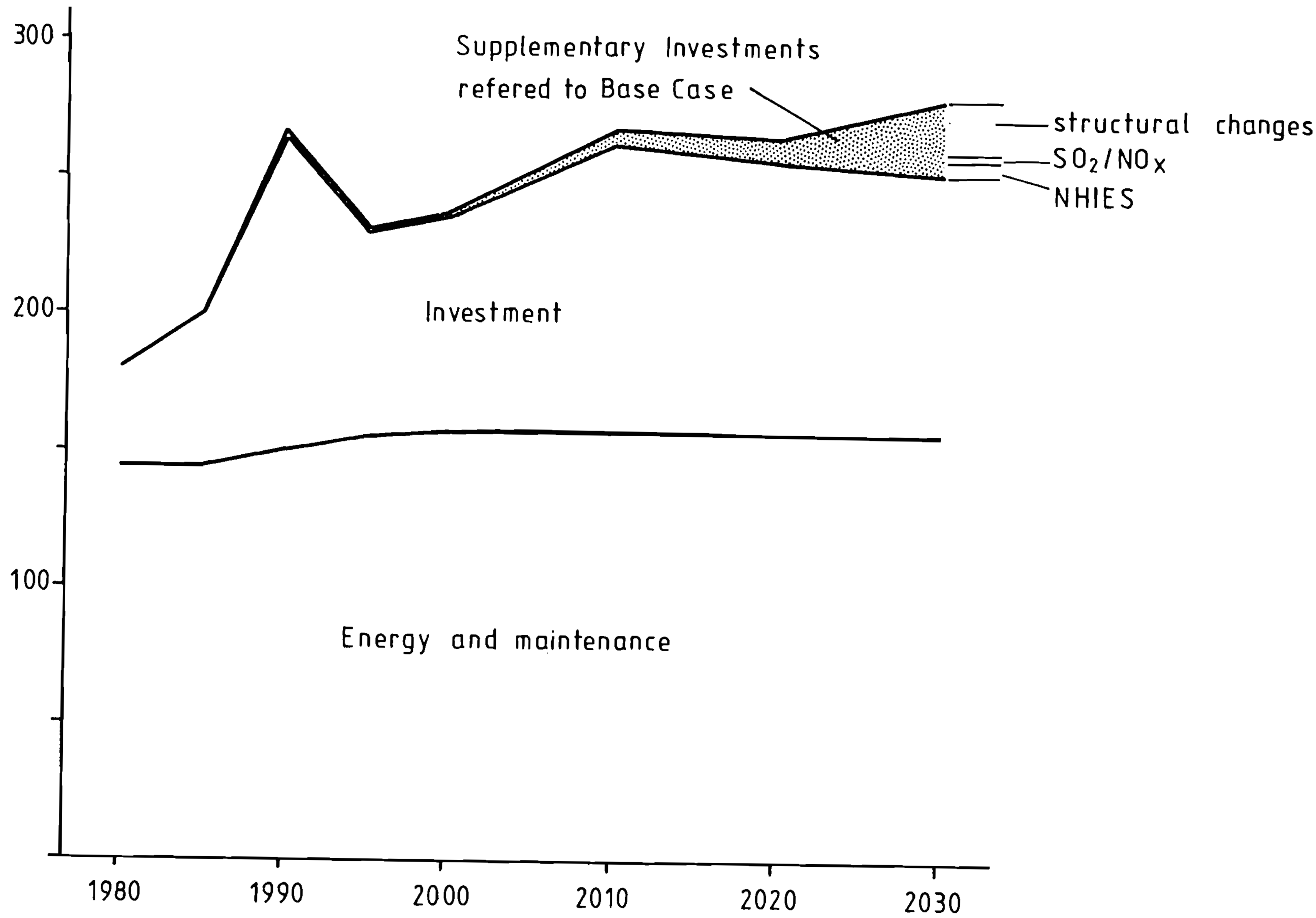


Fig. 10: Case 5: System Costs per Year (10^9 DM/a)

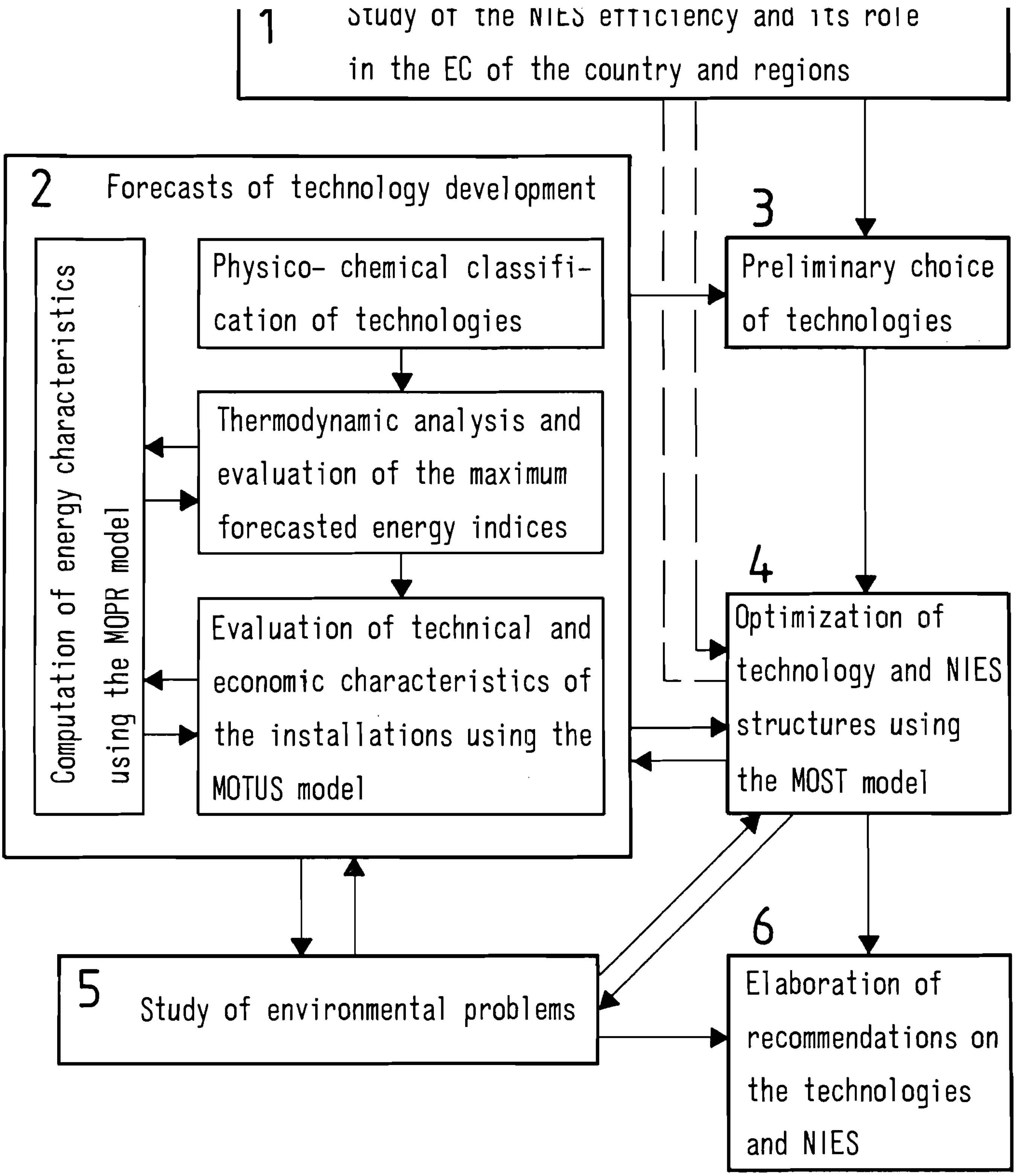


Fig. 11: Framework of SEI reseach on integrated energy systems

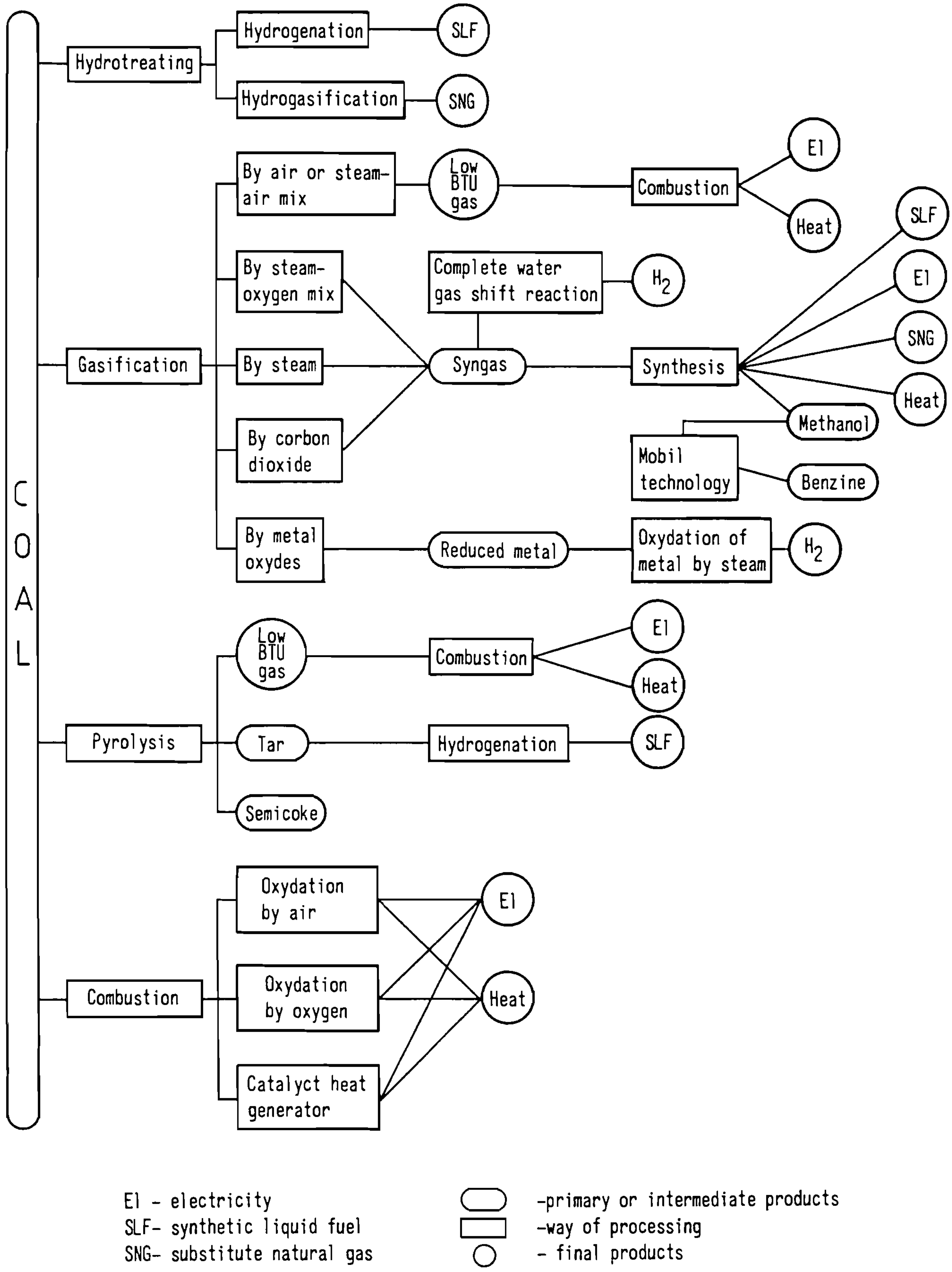


Fig. 12: A variant of the physico-chemical classification of coal utilization processes

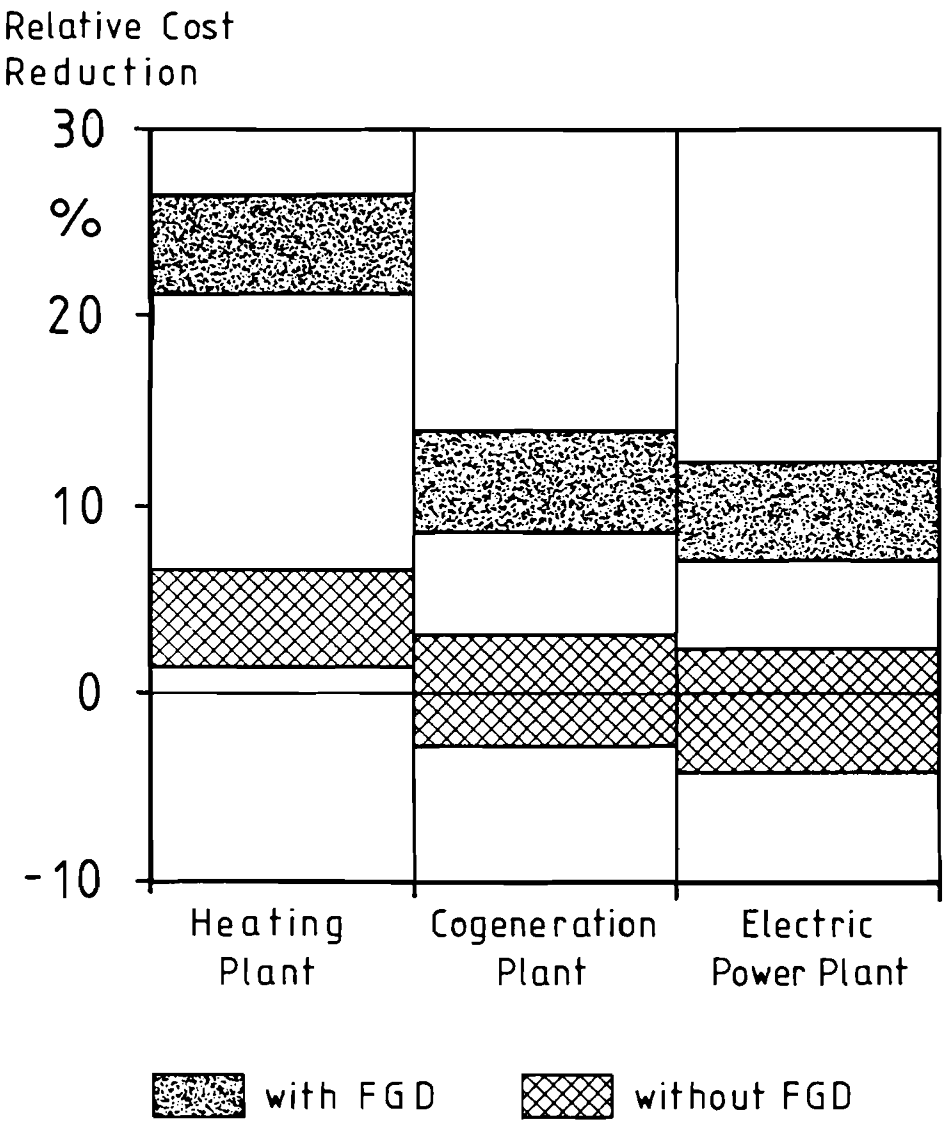


Fig. 13: Production Cost Savings:
Catulytic heat generation versus
conventional technology