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THE STUDY ON THE ROLE OF VERY HIGH TEMPERATURE REACTOR AND NUCLEAR PROCESS HEAT UTILIZATION IN FUTURE ENERGY SYSTEMS

—IMPLICATION IN ENERGY, ECONOMY, AND ENVIRONMENT OF JAPAN—

November 1987

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The objectives of the systems analysis study on "The Role of High Temperature Nuclear Heat in Future Energy Systems" under the cooperative research program between Japan Atomic Energy Research Institute and the Massachusetts Institute of Technology are to analyze the effect and the impact of introduction of high temperature nuclear heat in Japanese long-term energy systems aiming at zero environmental emissions from view points of energy supply/demand, economy progress, and environmental protection, and to show the potentials of involved technologies and to extract the associated problems necessary for research and developments.

This report describes the results being obtained in these three years from 1985. The present status of our energy system are explained at first, then, our findings concerning on analytical approach, method for analysis, view points to the future, scenario state space, reference energy systems, evolving technologies in it, and results analyzed are described.

This report was distributed at ICIES/IIASA meeting held at IIASA, Austria on July 13, 1987.

* COSMO Oil Campany.

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Keywords: HTGR, Nuclear Heat, Total Energy System, IES,
System Analysis, Scenario Analysis, Structural Analysis
Energy-Economic Analysis, Energy-Environment Analysis

将来のエネルギーシステムにおける高温ガス炉と核熱利用の役割に関する研究

ー我が国のエネルギー，経済，環境に於ける位置づけー

日本原子力研究所動力炉開発・安全性研究管理部
安川　茂・萬金　修一・佐藤　治・田所　啓弘
中野　泰行・永野　隆夫・山口　和夫・上野　精一

（1987年10月19日受理）

日本原子力研究所とマサチューセッツ工科大学との国際協力研究の下に行ってきた「将来のエネルギーシステムに於ける高温ガス炉と核熱利用の役割」に関するシステム分析研究の目的は，特に環境無排出を目ざす我が国の将来のエネルギーシステムに高温核熱を導入した場合のエネルギー需給，経済発展，環境保全に与える効果とそこでの役割を明確にすると共に，高温ガス炉と核熱関連技術の研究開発に於ける諸課題を抽出することである。

本報告書は昭和60年度から3年間にわたって行ってきた研究成果を，現状認識，アプローチ及び手法，分析の原理，シナリオ状態空間，トータルエネルギシステムと要素技術，エネルギー需給・経済・環境・要素技術の分析結果にまとめて報告するものである。

本報告書は1987年7月13日，IIASA（国際応用システム分析研究所）で開催されたICIES（国際統合エネルギーシステムコンソーシアム）／IIASA会議，において発表，配布された。

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1. Introduction

A High-Temperature Gas-Cooled Reactor (HTGR), of its core being composed of ceramic fuel, graphite moderator, and helium coolant, and of each material being resistive to high temperature and low in neutron absorption, has very prominent characteristics such as high-temperature heat production capability and low nuclear fuel consumption.

Due to large specific heat of ceramic fuel and graphite material, the time response of temperature rise in fuel and moderator at power excursion is very moderate and large negative reactivity coefficient of the core prohibits inherently large power excursion that causes severe core damage.

Moreover, if the reactor could be designed so as to remove the residual heat in the reactor core, most of which is the decay heat from radioactive nuclides in fuel and structural materials, released through the mechanisms based only on natural science laws, for instances, heat conduction and heat convection, the reactor, then, can be considered as inherently safe one. As this reason, many attentions have been given in this reactor especially after the TMI and the Chernobyl.

It is worthwhile for us to consider the role of HTGR in our future energy systems, because the high-temperature heat from HTGR can be utilized not only for electric power generation but also as process heat for processing carbonic fuel materials to produce synthetic gas fuels and/or liquefied fuels. In the latter utilizations, hydrogen plays a key role as an agent gas to reform carbonic fuel materials. And, in processing fuel conversion, various impurities such as sulphur, nitrogen, and heavy metals are removed from raw materials so that the process can contribute to clean fuel also. If we are proceeding to one step ahead in our consideration, we can consider hydrogen as a strong agent gas which can convert carbon dioxide into fuel materials again to make the recycle use of it.

As seen in the above, we can summarize the HTGR prominent characteristics in the followings: 1) high-temperature heat production capability, 2) inherently safe reactor characteristics, 3) low nuclear fuel consumption, 4) various possibilities of heat utilization such as electric power generation, process heat application to produce clean and convenient gaseous and/or liquefied fuels, 5) recycling use of carbon dioxide, etc..

The objectives of our study on "The Role of High Temperature Nuclear Heat in Future Energy Systems aiming at Zero Environmental Emission" are to analyze the effect and the impact of introduction of high temperature nuclear heat in Japanese long-term energy systems from view points of energy supply/demand, economy progress, and environmental protection, and to show the potentials of involved technologies and to extract the associated problems necessary for research and developments.[1] In the following chapters, first, we will explain the present status of our energy system, then, we will proceed to explain our findings concerning on analytical approach, view points to the future, scenario state space, reference energy system, evolving technologies in it, results analyzed, and expectation to the future.

2. Energy, Environment at Present

2.1 Energy Supply and Demand

The situation of energy supply and demand in Japan has changed remarkably in those years before and after the first oil embargo. The primary energy growths before 1973 were always over those of the GDP, but after that year they have never exceeded the GDP growth (Fig. 1-a)). In the supply side, oil dependency of the primary energy has been steadily shrinking, while the supply of alternative energy sources such as coal, gas, nuclear energy has been increasing, and the share of the domestic energy supply reached to 18.4% in 1985 from 10.6% in 1973 (Fig. 1-b)).

Inspecting the changes of energy demands in final sectors in those years, we could see that the demand in industrial sector has declined largely, while in transportation sector and in residential and commercial sector it has increased. Looking at the demand by kinds of secondary energy carriers, we could admit that the demand of oil products, especially of fuel oil, has declined largely while both gas and electricity has increased.

In electric power generation, the contribution of oil/LPG steam power plants has been lowering, but coal and LNG steam power plants and nuclear power plants have increased their shares. Among those, nuclear power plant contribution has steadily increased and in 1985 it was first over that of oil/LPG steam power plants and took 26.3% share of the total electric power generation.

Such structural changes in energy demand and supply as seen in the above have been due to the reduced economy, the energy conservation efforts, the promotion of fuel switching, and the industrial restructuring which aimed for both shifting product-mix to higher value-added goods and services and shifting production technology from heavy capital intensive one to lesser one but employing sophisticated technologies, for instances, electronics and robots. All of these have been experienced more or less in those years.

One quantitative analysis on such structural changes is exemplified in Fig. 1-c), where the effect is accounted for in the following order: (i) conservation efforts, rationalization, and efficiency improvements, (ii) active introduction of alternative energy sources such as natural gas, coal, and nuclear energy, (iii) shifting goods and services to higher value-added ones through increasing the weight of those industries as for assembling, for processing and for servicing instead of primary material production.

Fuel consumptions in various services [which can be categorized (i) as raw material, (ii) for boiler fuel, (iii) for various heating purposes except boiler, (iv) for power, lighting, air-conditioning, and others] since 1973 can be summarized in the followings: the share of the category (i) is in the order less than 3%; most of fuel for the category (ii) was fuel oil (heavy distillates of the grade C), but since 1980 some of it has been substituted by coal and recycle use of waste; for the category (iii), especially in cement industry the substitution of fuel oil by coal has been attained greatly, and in iron and steel industry the promotion of oil-less processing has been completed; almost all of the demand for the category (iv) is electricity and it has been steadily increased according to changes in products mix in industries.

2.2 Environmental Emission

In regards to energy-related environment matter, the concentrations of air pollutants in the ambient air are shown in Fig. 1-d) for past ten years, selecting SO_2, NO_2, CO as examples. SO_2 concentration indicated its peak value (0.059ppm) in 1962 but it has been declining year after year and reached to the level of 0.012ppm in 1984. This reduction was brought by shifting to low sulphur fuels and to the active introduction of desulphurization facilities for flue-gas. Concerning on NO_2 concentration, it has not always been reduced even though such countermeasures as denitrification facilities for flue-gas, low NOx burner, catalytic reduction for CO, HC, NO_X simultaneously for automobile exhaust gas have been widely introduced.

SO_X, NO_X emission releases and their emission coefficients of each industry are shown in Fig. 1-e). Even though the emission coefficients in iron and steel industry as well as in electric utility have been restrained in rather low value comparing with other industries, the total releases of these two sectors are large on the contrary because of large heat duties. In regards to facility base release, steam power plants, industrial boilers and furnaces share the major part of it.

3. Approaches and Methodologies

3.1 Study Subjects and Model System

This System Analysis is based on the system engineering approaches and methodologies which are composed of the identification, estimation, and decision making theories etc. and data base, and consists of four study subjects for the purpose of maintaining the reality and continuity through long term from the year 1980 to 2020 and for having robustness and resilience for future uncertainties.

The first subject is to generate energy-economic scenarios based on the analysis on the energy-economic-social progress of Japan by using mathematical models. The purposes are to draw future social system in multi-dimensional time space defined by economic, environmental, energy variables and to obtain image figures, then to estimate and to evaluate the space region where image figure will develop towards future, including uncertainties.

The second subject is the energy technologies characterization; that is to investigate and estimate macro technological and economical characteristics of future technologies of total energy systems in Japan and to draw them (named as 'Reference energy system') in a flow diagram based on objects and characteristics within reality and continuity of present status of element technologies.

The third subject is to analyze the impact, contribution, and the role of element technologies within future society of Japan. That is to construct optimization problem under the minimization of objective function which is composed of total system cost, cumulative amounts of imported oil and natural gas and total amounts of environment effluent. The results of case studies are analyzed in such view points as effective utilization of energy, value added fuel, and zero emission.

The fourth subject is to investigate the status and to identify the path and directions in research and development of VHTR and nuclear heat utilization technologies which could be able to have large roles in the results of analysis.

While, at JAERI, mathematical model system and data base have been of air pollutants in the ambient air are shown in Fig. 1-d) for past ten years, selecting SO_2, NO_2, CO as examples. SO_2 concentration indicated its peak value (0.059ppm) in 1962 but it has been declining year after year and reached to the level of 0.012ppm in 1984. This reduction was brought by shifting to low sulphur fuels and to the active introduction of desulphurization facilities for flue-gas. Concerning on NO_2 concentration, it has not always been reduced even though such countermeasures as denitrification facilities for flue-gas, low NO_x burner, catalytic reduction for CO, HC, NO_x simultaneously for automobile exhaust gas have been widely introduced.

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While, at JAERI, mathematical model system and data base have been developed for the purpose of providing analytical tool for the systems analysis on nuclear technologies in interdisciplinary problems. At present, these model groups have been integrated into Energy-Economy-Environment (E^3) Model System.[2]

The Integrated E^3 Model System, as shown in Fig. 2, consists of the following four model blocks. The first model block, called as the dynamic scenario generation block, can serve to analyze and construct long-term scenarios on socio-economy evolution based on system dynamics technologies and econometric theories.

The second model block, as a part for analyzing structural nature of the energy-economic interaction system, installs the MARKAL model and the input-output econometric model. The third model block handles power reactor strategy and long-term fuel cycle analysis. The fourth model block treats cost-benefit-risk analysis and various data bases are included in it.

3.2 Mathematical Models

Corresponding to the study subjects mentioned above, we extract mathematical models and data bases from the 1st block and the 2nd block of the model system. For the first study subject, we adopt Long-Term Macro Econometric Model LTMEMO which can produce macro economic scenarios of Japan through the year 2020.[3]

This model is composed of such programs as related social and economic statistic data treatment programs, identification and estimation programs of various econometric parameters of structural equations, a simulation program for future projections, and a reference econometric program. The model has also social and economic statistic time-series data files and the computer program code EEMVAR which identifies multi-variable auto-regressive models based on the results of causality study on data in the system surroundings.

The reference model is composed of 75 nonlinear structural equations, 87 definitive equations and 70 exogenous variables, and belongs to an equilibrium time-invariant, fixed structural, descriptive, and econometric model category. Frameworks of the reference model were deviated based on the combination of Keynesian theories and Neo-classical theories and has the structure shown in Fig. 3-a).

For the purpose of projecting and analyzing demand/supply situation of energy through the long-term and of generating energy scenarios, mathematical model named ENERGYSD has been selected. This model has been developed referring to the Energy Policy Model "FOSSIL-2" developed by DOE in the U.S.A.. Using the SD (System Dynamics) modeling technique, the model was designed as an energy supply side model composed of non-linear differential equations describing the actual balance of money-energy flow and stock in total energy system of Japan.[4]

The decision making method of the model is based on the allocation and adjustment of energy and money flow depending upon demand and supply balance in market of various forms of energy and its products. Therefore, the model is divided into two parts, one determining the demand for energy carriers and the other representing their supply structures and is composed of financial sector, production sector, import and stock sector, and resource sector in each demand/supply balance point as shown in Fig. 3-b).

For the case study of optimization problem in the third subjects, we adopt multi-period market allocation model MARKAL. This model developed and improved in OECD/IEA/ETSAP is a demand-driven type model to provide optimum market allocation of energy technologies and energy carriers by utilizing the LP method. We facilitated the latest BNL/KFA Version-2 [5] as one of the joint member institute.

Optimal capacity and activity of each technology within total energy systems toward the year 2020 can be obtained under the given useful energy demand boundaries in 35 demand sectors and 34 kinds of constraints and balance equations.

For the analysis on the degree of the substitutability and complimentarity among factor inputs under the change of energy technologies configuration, the E-I/O(TRANS) model is adopted. This model is a multisectoral energy-economy interaction model to analyze structurally the long-term evolution of energy-economy systems and to estimate the impact being brought upon energy technologies from the rest of an economy system.

The model has two sub-models, i.e. E-MATRIX and TRANS-I/O. The former sub-model incorporates the framework of energy matrix analysis to allow combined calculation with MARKAL, and inter-industrial transactions are determined by the econometric I/O methods with variable coefficients in the latter sub-model. The framework of TRANS-I/O is shown in Fig. 3-c), and is based on the transcendental-logarithmic functions and econometric definitive relations.

As the environment problems have their origin in man's activities in nature, their subjects and characteristics are broad and various, however, the acid rain and the greenhouse effect become one of noteworthy problems among them. Therefore, in this analysis, the effluents are considered to be represented by amounts of SO_X, NO_X, and CO_2 emissions and the methods of countermeasure are restricted within the range of structures of total energy systems and emission control technologies; e.g. fuel substitution, energy-saving, fuel transformation, improvement in efficiency, introduction of new technologies in energy system and in emission control technologies, etc..

The analysis is based on the results obtained from optimization calculation by MARKAL, and the objective function of MARKAL is modified by adding performance indices of emission after calculating each column coefficient. As the result of the modification, the trade-off analysis between the total system cost including cost of emission control technologies and the amounts of effluent has been available [6].

3.3 Procedure and View Points

Making the most use of these mathematical models, we have carried out the study subjects along with the working procedure and present flow chart of task procedure in Fig. 4. As far as the fourth study subject is concerned, the results of investigation are mentioned in the other reports and would be progressed in the form of technical assessments.

The task procedure in the flow chart is divided into four parts which are scenario generation, structural analysis, data acquisition and optimization case studies. Reflecting the results of the 1st and the 3rd parts of the procedures, the 2nd and the 4th parts have been carried out.

In the structural analysis, discussion view points of the study on the energy demand and supply are resources and stable supply, independency from crude-oil, cost-security trade-off, conveniency, conversion efficiency, utilization efficiency, nuclear heat utilization, change of supply structure, share of electricity and supply constraints.

Discussion view points of the analysis on the economics are future cost of system, composition of cost, economic structure, marginal cost (shadow price), input structure of energy, value-added, technology costs and cost variation.

Discussion view points of the analysis on the energy-environmental problems are fuel substitution, fuel conversion, emission-control technologies, trade-off between cost and effluent, cost effectiveness, transition of effluents, effect of structural change of energy system, composition of amount of electric generation, and recycle use of effluent.

The Role of VHTR and Nuclear Heat Utilization Technologies are discussed in over-all analysis and the transition in the adoption process of element technologies in total energy systems are also reviewed in both cost/security trade-off case and cost/effluent trade-off case.

4. Principles for Analysis and Scenario State Space

4.1 Principles for Analysis

At the start of our four study subjects presented in the previous chapter, principles for the analysis are established for the purposes of finding out analytical answers on the role of VHTR and nuclear heat utilization technologies. These principles are composed from the views for future; how our future energy systems should behave, or what pattern of the behavior could be desired for Japanese future.

The first principle is continuation of energy conservation and promotion of effective utilization of energy. Such possibilities as conservation, improvement in efficiency and effective utilization of energy should be found out in the design of energy systems or in prospects of R&D in element technologies.

The second principle is endevour to transform energy carriers to high value added one. Transition is occuring in the age where fossil fuels are utilized in the form of as they are. If they could be utilized in or transformed into suitable form for future value criteria, the value of restrictive resources could be increased and could derive the expansion of equilibrium economy.

The third principle is to increase the adaptation to the environment including safety and convenience. The environment is also one of restrictive resources and the importance of the value in the interaction between man and nature becomes large. Energy should be produced and utilized in the systems which would aim at zero emission.

In other principles, economy and stable supply should not be lacked for, because these are fundamental characteristics laid in the interaction between energy and society. Necessary condition for the analysis based on these principles mentioned above is that prospects on future society of Japan should be reflected sufficiently on boundary conditions of structural analysis.

That is to say, it is necessary for us to generate scenarios which could compensate such weak points as dynamic characteristics, nonlinearlities, stabilities, continuities, and realities in the results from the LP (Linear Programming) method as the one of main algorithms in structural analysis.

4.2 Long-term Macro Economic Scenarios

The present situations of the world economy are very hard. Suppression economy and declining of growth are being fixed not only in the world (shadow price), input structure of energy, value-added, technology costs and cost variation.

Discussion view points of the analysis on the energy-environmental problems are fuel substitution, fuel conversion, emission-control technologies, trade-off between cost and effluent, cost effectiveness, transition of effluents, effect of structural change of energy system, composition of amount of electric generation, and recycle use of effluent.

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4.2 Long-term Macro Economic Scenarios

The present situations of the world economy are very hard. Suppression economy and declining of growth are being fixed not only in the world but also in Japan. In these situations, we can not expect high growth of economy in near future, moreover, the present economic theories seem to lose the persuative force for further economic growth. Therefore, it is natural and reasonable to prospect future economic situation in the low growth but stable figures.

Long-term macro economic scenarios of Japan until the year 2030 were generated by use of LTMEMO. As the result of simulation study, two sets (α and β) of time series values for the 162 endogeneous variables and economic indices are obtained with which macro economic scenario region is defined as shown in Fig. 5-a). The growth rates of the national expenditure in the scenario α are 3.4%, 2.9%, 2.0%, 1.5% and 0.6% respectively for each 10 years from 1980 to 2030. In the scenario β, they are 2.7%, 2.4%, 1.3%, 1.0% and 0.4%.[7]

Scenario α is of the limitted growth type, in which low but stable growth is prospected to continue until around the year 2010, and thereafter the growth rate declines rapidly. It prospects the stable growth of the economy until the year 2010 reflecting high estimation of its recovery force from damages after the oil crisis and its steady growth in recent years. However, the economy is obliged to turn into the limitted growth economy after the year 2010 missing substantial expansion of consumption and investment under the pressure of trade friction and limitted availability of resources.

Scenario β is of minimum growth type, which aimed at estimating the lower limit of future economic condition by evaluating the real growth ability of economy rather lower even at present. While the scenario α prospects moderate and stable economic growth for mid term, quite low growth is prospected from now in the scenario β. The rate of gross world products begin to decline from 1980. The assumption on the growth rate of world import as low as 2%/y seems excessively low. Suppression of prices will be introduced by the economic control policy against inflation, and slowing-down economy is conducted from now by the household, the industries, and the government.

The composition of the gross national expenditure for both scenarios is presented in Fig. 5-b) at every five years from 1980 to 2030. The future economic life of the nation in these scenario can be recognized from Table 1. These figures explain clearly the nature of the two scenarios, i.e. the growth pattern of the scenario α is of the Keynesian-type, while the scenario β is of the Neo-classical theory type.

The comparative feature is that in the scenario α the export-import shows high growth until the year 2010 but declines thereafter, while in the scenario β the growth is low but steady. In the scenario α, reduction in the export-import influences directly the growth of the GNE, on the other hand, the investment for the private sector continues to increase even after the year 2010. This fact is corresponding to the increase in the export and the expansion of the final consumption in the private sector, and represents the nature that the growth is led by an effective demand. In the scenario β, each component of the GNE shows the tendency "growing slowly but steadily".

4.3 Macro Energy Scenarios

On the other hand, long-term macro energy scenarios of Japan until the year 2030 were generated by use of ENERGYSD based on the results of analysis on the macro economic scenarios through the value of GNP, the value of GNP elasticities for energy demand, prices of energies, and price elasticities for energy demand.

Fig. 6-a) shows the projection of the realized GNP, primary energy supply, final energy demand and primary energy supplies of each energy kind. The symbols α, β in the right hand side column show that the curves are corresponding to each economic scenario α, and β. The electricity in the primary energy supply is composed of hydropower generation, nuclear power generation and geothermal power generation because of traditional accounting rule in Japan. Fig. 6-b) shows the projection of demand of total final energy and of each energy.

All of the simulation studies start at 1965 by setting initial values of 1965 and the start point of the projection is 1980, because exogeneous values for the term from 1965 to 1980 were settled by statistic data and by estimated values for the term from 1981. By these treatment, we can check errors not only in parameters used in the model but also in setting exogenous variables. Comparing the values of the term from 1965 to 1980 in Fig. 6 with statistic data, we can find satisfactory agreement between them and can have good trust in the results of simulation studies. [7]

The observation of projections after 1980 shows that the average growth rate of GNP during 1980-2030 is 2.7% in the scenario α and 1.7% in β, and that the growth rate of energy supply is 1.1% and 0.8% respectively. The ratio of the energy consumption per GNP at 2030 to the value at 1980 is 0.55 in the scenario α and 0.60 in the scenario β. This fact means that such activities in energy field as energy-saving, energy-conservation and the transitions of structure from high energy intensive industries should be promoted for the future.

In spite of low setting of GNP multiplier for oil demand, the reducing level of oil supply is not so large in Fig. 6-a). From this results, we observe that oil is treated as cheaper energy than electricity and gas, even in the assumptions that the growth rate in price of imported crude oil is about 2.5%/y in high case. In the case of coal, it's share in the total energy supply rises rapidly despite that price multiplier of coal is not high. The reason of this phenomena may be explained by Fig. 6-b) which shows large amount of coal will be used for conversion to electricity and gas.

Comparing the projected values of final energy demand from 1965 to 1980 with statistic data shows good agreement except that the peak value of the projection in 1979 is a little lower than the statistic data. The shares of oil, coal, gas and electricity in the total energy in Fig. 6-b) are 59, 13, 14, 14% respectively at 1970 and show good agreement with statistic data, and they become 28, 25, 16, 31% respectively in both scenario α and β at the year 2030.

As a part of representative values transferred from values in these scenarios to input data of MARKAL for structural analysis, indices of GNE growth, final energy demand, useful energy demand, and prices of imported energy are shown in Table 2 and Fig. 7 respectively. Prices of import energy are also exogenous variables for models used for scenario generation, however, they are adjusted and decided reflecting consistencies with the situation of macro economy-energy scenarios.

Observing the results of scenario generation mentioned above, the economic scenarios generated in this study are considered to belong to the low-growth type.

We should aim at developing attractive energy technologies and systems that have abilities to conquer recent tendencies to adopt conservative technologies from the view point of low cost. It would be worthwhile in true senses to develop technologies which could benefit the society in the mid 21st century, therefore, it is one of necessary conditions to adopt low-growth scenario as well as to adopt hard principles for analysis.

5. Energy System and Technologies

5.1 Reference Energy System

The flow diagram of the reference energy system for the analysis is illustrated in Fig. 8. The figure represents energy sources, energy technologies, and possible flows of energy carriers within the system. The entire system is largely divided into three component systems for primary energy supply, transformation, and end-use, each of which is designed to fulfill its function in order to realize, as a whole, principles and objects of the system before mentioned.

The primary energy supply system deals with imports, domestic productions, and stockpiles of energy carriers. The essential subject for this system is diversification of energy sources to ensure stable supply of energy. In addition to expanded uses of coal and nuclear energy, significant contribution of new energy sources is expected, in particular, of imported liquefied coal, geothermal energy, and solar energy.

The transformation system consists of two types of energy technologies, i.e. conversion technologies to produce electricity and/or low temperature heat and process technologies to produce, transport, and store energy carriers other than the aboves. The main subjects for conversion technologies are switchover from utilization of fossil fuels especially of oil products, improvements in conversion efficiency, and promotion of waste heat utilization.

New technologies prepared for the system are non-fossil technologies such as advanced nuclear reactors, geothermal, solar photovoltaic, high-efficiency technologies such as coal low BTU gasification & combined cycle, natural gas combined cycle, and cogeneration technologies by nuclear and fossil fuels.

The key subject for process technologies is to produce clean, convenient, and low price fluid fuels from low grade resources. Among various candidates, coal liquefaction and gasification seem to be most promissing within the time horizon of this study. Three types of liquefaction technologies are considered, i.e. two direct hydrogenation technologies producing either heavy liquids or light liquids and an indirect liquefaction technology using the Fischer-Tropsch process. The plants for the first two technologies are assumed to site abroad. Liquefied coal produced by these technologies is, when necessary, refined or converted into fuels of proper grade and delivered to end users applying existing infrastructure for oil products.

Two types of coal gasification technologies are considered in the system. One is steam-gasification to produce medium BTU gas with H_2/CO molar ratio 0.83 by utilizing pure oxygen. The gas produced is used as an industrial gas, or for producing methane, or for producing hydrogen. Another is hydrogasification to produce SNG by utilizing hydrogen and oxygen provided externally. The well-known difficulty in these technologies is high prices of hydrogen and oxygen produced by conventional technologies. Therefore the coal gasification system is linked to the high temperature nuclear heat utilization system which possibly offers hydrogen and oxygen in much lower prices.

conditions to adopt low-growth scenario as well as to adopt hard principles for analysis.

5. Energy System and Technologies

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The end-use system consists of 35 demand sectors and 164 demand devices. Useful energy demand is specified for each demand sector in terms of annual quantity and its seasonal and diurnal distribution. For effective utilization of energy and for expanding possibility in fuel selection, new demand devices are prepared such as heat pumps, solar heating devices, electric cars, hydrogen cars, hydrogen airplanes, and nuclear ships. For enhancing fuel switching in industry, concerned are application of reducing gas and high temperature nuclear heat in iron & steel making, hydrogen use in chemical industries, substitution of boiler fuels by nuclear process heat.

The energy source of the high temperature nuclear heat utilization system is VHTR. The main raw materials are coal, natural gas, water, and air. The system produces electricity, high and medium temperature process heat, hydrogen, and other clean and convenient synthetic fuels by employing three fundamental processes, i.e. reforming, separation, and synthesis. The representative technologies involved are methane reforming, reducing gas production, thermochemical hydrogen production, high temperature electrolysis, synthetic gas separation, air separation, methanol synthesis, gasoline synthesis, and thermochemical heat pipe.

One of the behavioral objects, zero emission to the environment, gives an additional function to the above system. A part of carbon dioxide involved in flue gas of fossil fuel combustion equipments is recovered and re-used as a carbon source. The technologies concerned are thermochemical CO_2 splitting utilizing high temperature nuclear heat, CO_2 reforming of methane, methane and methanol synthesis using CO_2 as a raw material.

5.2 Technology Characteristics and Constraints

Characteristic data have been prepared for all technologies involved in the reference energy system. The data have been established in this study specifically for high temperature nuclear heat utilization technologies, coal gasification technologies, and several other technologies, while those established in the Energy Technology Systems Analysis Project under the International Energy Agency are utilized for the rest of the technologies.[8] Main technical and cost data are listed in Table 3 for representative transformation technologies. As for conversion technologies, included in the table are important, existing and new technologies for electric power generation. While, coal conversion and high temperature nuclear heat utilization technologies are listed out as process technologies.

Among technical data in Table 3, availability represents an upper limit of annual average. For some conversion technologies, the values are given seasonally and diurnally according to their characteristics. Efficiency refers to the ratio of output energy to input energy evaluated in terms of gross heating value. All cost data are expressed in 1980 US dollars. Values are given per unit of capacity, activity, or energy quantity. These quantities are defined based on output energy in the case of conversion technologies, while based on input energy generally in the case of process technologies.

Costs of future technologies have in general large uncertainties. They may be reduced substantially after unexpected breakthrough of technical barriers, while may increase facing unforeseen difficulties. However, cost data for this study do not reflect any factors for which quantitative evaluation of influences is difficult. Exceptions to this are solar photovoltaic and coal liquefaction technologies which have huge potential market and also apparent possibility in reducing costs through mass production and technical progresses. Similar approach is taken also in preparing technical performance data. Energy efficiencies of demand devices, not listed in this table, are assumed to increase generally throughout the time horizon in expectation of continuous efforts to improve them.

Various constraints are given externally to energy technologies and energy carriers involved in the reference energy system through optimization studies in order to ensure "continuity" and "reality" in the evolution of energy systems, and also to take into account miscellaneous non-technological factors. Important for energy technologies are the possible date of introduction in a technical sense and the constraint on capacity. While, annual availability is constrained for each source of primary energy. This constraint has been determined based on the amount of world resource, past imports, past domestic production levels, and domestic policy on future production.

The constraints for high temperature nuclear heat supply and utilization technologies and for coal conversion technologies have of great importance in appreciating the results obtained in this study. The possible date of introduction for VHTR and its heat utilization technologies is determined as the year 2010 assuming successful R&D and completion of demonstration early in next century. Implementation level of VHTR is limitted to 10GWt (low demand scenario) or 12 GWt (high demand scenario) at the year 2020. This level has been determined considering realistic pace of construction, and not the size of market. The market size of VHTR at that year may be larger or smaller than this depending on technical and economic performances of utilization technologies. Constraints are not given in principle on implementation levels of utilization technologies.

Coal liquefaction plants are assumed to be available from the year 1990 considering that a part of relevant projects has been already started. The installed capacity at the year 2020 is limitted to 135 million ton (coal)/year for heavy liquids production and half of it for light liquids production. Indirect liquefaction technology is assumed to be available after the year 1995. The possible implementation level of this technology is expected much lower than the above technologies.

Introduction of coal steam-gasification is assumed to be possible after the year 1990 considering enough progress of R&D on associated technologies. The capacity is expected to expand significantly after the year 2000. The upper limit for the installed capacity at the year 2020 has been determined as 45 million ton (coal)/ year. Coal hydrogasification is assumed to be available after the year 2000. Though the installed capacity at the year 2020 is limitted to the same level as that of steam-gasification, it is also limitted indirectly by availability of cheap hydrogen.

5.3 Emission Data Base and Control System

The data on environmental emissions are categorized into conversion technlogies, process technologies, and demand technologies for environmental emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x) and carbon dioxide (CO_2). We have collected the data on emissions at 1980 for each technology, as shown in Table 4.[6]

Concerning the data on SO_x, emissions of energy technologies were calculated from the data of sulfur content in fuel which are provided by Environment Agency[9], and compiled taking into account the status of installation for flue gas desulfurization equipments at 1980[10]. We adopt the following assumptions to collect the data on SO_x: i.e., a) SO_x reduction equipments have been already installed for conversion and process technologies, b) H_2S gas emitted from geothermal power plants to ambient air is regarded as SO_x, c) no consideration for SO_x from material used in industries, d) effluent gas from low sulfur fuel is and will be emitted to ambient air without any countermeasures.

The amounts of NO_x emission vary with energy technologies even if same fuel is used, because NO_x formation depends on both fuel and types of combustion. We adopted the representative data on NO_x emission as coefficients of energy technologies for each energy carriers[9]. We assumed that denitration equipments have been installed with only conversion technologies by 20% as emission control technologies, but not installed with process technologies and demand devices. CO_2 emission coefficients were calculated from carbon content in fuel (coal, oil and gas)[11].

As SO_x reduction equipments, we imagined flue gas desulfurization, and classified them into each of four grades by amount of flue gas and SO_x concentration respectively, furthermore we classified into three grades by desulfurization rate as shown in Table 5-a). In this case we considered conversion and process technologies as the super large scale. The scales of demand devices were classified based on the data provided by Environment Agency[9].

As NO_x reduction equipments, we supposed flue-gas denitration, and classified into each of four grades as in the case of SO_x, and classified moreover by SO_x concentration coexisted (Table 5-b)). In NO_x case, we considered conversion and process technologies as super large scale, too.

Main technical and cost data for desulfurization and denitration equipments are shown in Table 5-c), d). Costs for SO_x reduction equipments depend on the factor of their scale, SO_x concentration and desulfurization rate. While equipment scale is considered for capital cost, all factors are considered for O&M cost. In residential and transport sector, low sulfur fuel (diesel oil and fuel oil) is supposed to be used to control SO_x emission. We considered the desulfurizing cost of the fuel as reduction cost for SO_x emission.

Costs for NO_x emission control depend on the factor of their equipment scale, NO_x concentration, and SO_x concentration coexisted. The difference of SO_x concentration affects the volume of catalysts and its life. The higher the concentration is, the more expensive capital and O&M cost are. In residential and transport sector we adopted the highest cost data as NO_x emission control, because the cost evaluation is not yet performed sufficiently.

Reflecting the concept and data on emission control technologies, emission control systems are built up and are added to the reference energy system. Fig. 9 shows the outline of the system; a) shows the SO_x control system and b) shows the NO_x control system.[6]

All SO_x emissions from conversion and process technologies are categorized by their characteristics to following three groups; i.e. i) normal sulfurization group, ii) low sulfur and gas, and iii) high sulfurization group.

Flue-gas of category i) can pass through 50% ~ 75% desulfurization equipments, flue-gas of category ii) is emitted to atmosphere without control, and category iii) can pass through 70% ~ 90% desulfurization equipments and again can pass through 50% ~ 75% reduction equipments.

As far as SO_x emission from demand devices, four categories are also assumed; i.e. i) flue-gases from demand devices in industry and commercial sector can once pass through 70% ~ 90% reduction equipments and again can pass through 50% ~ 75% reduction equipments.

Low sulfur flue-gas in residential and transport sector is emitted without control, and part of flue-gas in same sector can pass through small scale equipment, and part of flue-gas in same sector can pass through middle scale equipment.

NO_x control system (Fig. 9-b)) has almost similar structure as SO_x control system. Low NO_x concentration flue gas from conversion and process technologies can only pass through 50% ~ 80% reduction equipments. High NO_x concentration flue-gas from conversion, process, and demand technologies can pass 80% NO_x reduction equipment once and can choose to pass 50% ~ 80% reduction equipment again. NO_x concentration flue-gas from residential and transport sector can pass 80% NO_x reduction equipment. All of the flue-gas from element technologies can select whether they should pass through reduction equipments or avoid to pass through these emission control equipments depending upon the objective function.

6. Analytical Results

6.1 Energy Supply and Demand

The analysis has been carried out through optimization of the reference energy system over the period 1980-2020 under the long-term economy and energy scenarios described before. The basic analytical cases consist of four cases with combinations of low and high scenarios both for energy demand and energy price. Two fundamental indices have been applied for optimization, i.e. a total discounted system cost P and a cumulative amount of oil and natural gas imports S. The latter index represents security of supply considering economic risk of depending these scarce and unfavorably distributed sources. Objective functions are prepared combining P and S with different importances between system cost and supply security. Here two objective functions have been utilized, i.e. P and $QP = P + \alpha S$ (with $\alpha = 3$ \$/GJ; a premium for oil and natural gas prices). The results mainly on the low demand/high price-minimum QP case are described below.

The main subject in energy supply and demand is, as already described, to ensure stability of energy supply through changes of the structure depending excessibly on imported oil. The results indicate significant contribution of steam coal, nuclear, and renewable energy in this regard. Fig. 10-a) shows long-term transition in the structure of primary energy supply. Dependency on oil reduces to 12% in the year 2020, while steam coal, nuclear, and renewable energy share the substantial amount of energy supply. Increases in steam coal utilization lead to necessarily the concern about environmental influences. However, this figure also indicates no increase in total fossil energy supply through substitution of oil products by synthetic fuels from coal, and expanded supply of nuclear and renewable energy to meet increasing demand for energy.

The structure of energy consumption shows transition as indicated in Fig. 10-b) reflecting changes in requirements by end-users and in relative prices of energy carriers. Electricity largely increases its share in total final energy consumed from 15% in the year 1980 to 26% in the year 2020 mainly due to structural changes in industy, increase in demand for air-conditioning and power in the residential & commercial sector, and introduction of electric cars in the transportation sector. Renewable and again can pass through 50% ~ 75% reduction equipments.

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The demand for convenient fluid fuels is satisfied through changes of their sources from expensive oil and natural gas to cheaper coal. The fuel types required by the end-use sector also show the transition from a heavy fuel oil to light fuel oil and gas based on decreases in relative shares of industry, especially of heavy industry. The growth of total final energy consumption decreases after the year 2020. This is due to, in addition to general improvement in energy efficiency of demand devices, increasing penetration of high efficiency electric devices and appliances including heat pumps.

Effective utilization of energy is another fundamental subject for future energy systems. The efficiency of an energy system can be evaluated in terms of transformation efficiency (= primary energy supply/final energy consumption), utilization efficiency (= final energy consumption/ useful energy demand), and overall efficiency (= transformation efficiency times utilization efficiency).

The ranges of efficiencies for energy systems optimized in all analytical cases are shown in Fig. 11-a). Utilization efficiency increases with time, while transformation efficiency decreases. Overall efficiency shows a slight increase. The increase in utilization efficiency is based on the reason described just above. The decrease in transformation efficiency is due to the two main reasons; (a) rather slow progress in improvement of thermal efficiency in electricity generation despite increasing share of electricity in secondary energy, and (b) technologies to produce liquid fuels from oil refinery to coal liquefaction. Accordingly, in order to realize more effective uses of energy, strong efforts should be made in particular to improve efficiency of electricity generation and to promote cogeneration of electricity and heat.

Focus is now given on the utilization of nuclear energy, especially of high temperature nuclear heat, within energy supply-demand structure outlined above. VHTR is introduced to its upper limit in every analytical case producing high temperature heat of 4.9 (low demand) or 5.9 (high demand) million ton OE/year in the year 2020. It is utilized mainly in (a) electricity generation by helium gas turbines and steam turbines, (b) reducing gas production and its heating for iron and steel making, (c) hydrogen production through steam reforming, (d) medium temperature prcoess heat production employing thermochemical heat-pipe, and (e) hydrogen production through high temperature electrolysis and thermochemical process. An example of nuclear energy utilization is shown in Fig. 11-b). The share of high temperature nuclear heat in total primary energy supply is still quite small within the time horizon up to the year 2020. However, its indirect contribution on oil substitution is not small through providing relatively cheap hydrogen and oxygen for use in coal conversion.

For the purpose of examining the resilience and sensitivity of the result obtained above, trade-off relationships between total system cost and security, and the effects by the change of constraints are analyzed. Results are shown in Table 6 and Fig. 12. As the security value in high demand case is higher than that in low demand case, unsubstitutable oil demands exist more in high demand than in low demand. From the comparison of the slope of trade-off curves between high demand and low demand, it is clear that we cannot be free from the problems of oil import even in the year 2020, if we wish high growth in future economy.

From elasticity point of view, these curves indicate similar characteristics not only in price elasticities, but also in demand elasticities. This means that scenario regions in demand and price are not too large nor too small, and proves that macro energy-economy scenarios could be generated within suitable region including the structural change in future, and therefore implies that the results obtained from the low-demand and high-price scenario can represent the characteristics of other scenario case.

It should be noted that the amount of nuclear is almost constant both in high and low price scenario, however, shows a little change in each demand scenarios. It decreases a little in security case at high demand and increases a little at low demand case during transition from cost to security. This gives the conclusion that nuclear can obtain superiority only from economic view points, because the demand structure of the energy system can not permit for oil fuel to be substituted by nuclear energy.

For examining the effects by the change of constraints, comparison between the results of calculation cases with and without constraints on amount of imported steam-coal in UHD/HP-QP scenario has been carried out. The cost-security trade-off curve of the case is shown in Fig. 12-b). From detail inspection of the results of each QP and QP* case, it becomes clear that LNG is substituted by coal in the case from QP to QP*, while oil is substituted by coal in the case from P to QP. Coal utilization in the case from P to QP* is increased by 12 times in the amount of coal gasification, 2 times in power generation, 8 times in direct use, and no change in liquefaction and coke oven. The introduction of coal utilization for gasification and of such nuclear heat utilization technologies as CO shift conversion, CO methanol synthesis is depended upon the cost and constraints of imported steam coal.

In summary, steam coal, nuclear, and renewable energy make significant contribution on future energy supply. The current role of oil is mainly substituted by coal, and total consumption of fossil fuels remains unchanged. These structural changes enhance stability and economy in the supply side, and at the same time satisfy fundamental requirements in the demand side for clean, convenient, and cheap energy. While, in order to use energy more effectively, strong efforts are required on improvements in efficiency of electricity generation and promotion of cogeneration. High temperature nuclear heat, through production of electricity, industrial process heat, and hydrogen, contributes directly and indirectly on substitution of oil.

6.2 Economics

Economic aspects of optimized energy systems are analyzed in this section from the viewpoints: (a) How are future costs of energy systems influenced by the structural changes in energy supply-demand? (b) How is competitiveness of high temperature nuclear heat and synthetic fuels? Then, based on the results by the E-I/O(TRANS) model, future positions of the energy sector in total national economy and possible evolution of technology costs under the structural changes in economy are analyzed.

The annual cost and its structure of the energy transformation system are shown in Fig. 13-a) for the analytical case with low demand/high price-minimum QP. The investment cost in this figure is the sum of those costs accrued at the start of operation. Of total transformation cost in 1980, 71% is shared by the fuel cost for import or mining of primary energy. The share decreases to 47% in the year 2020 with substantial increases in costs for construction, operation, and maintenance of energy facilities. The reasons are: (a) Expanding utilization of nuclear and renewable energy which require large investment and O&M costs compared with small fuel cost. (b) Large-scale implementation of coal conversion technologies which employs large-sized and complex equipments to produce clean and convenient fuels as substitutes for oil production.

Of total investment cost, more than a half is shared by conversion technologies mainly for generating electricity. On the contrary, process technologies share more than a half of total O&M cost. This is mainly because; (a) O&M costs of coal conversion technologies are high due to utilization of catalysts and chemicals, and (b) the increase in direct uses of coal is requiring larger cost for transportation and distribution. In this study the assumption is made on primary energy prices to rise in real term. Nevertheless, the results show only small increases in future fuel costs through successful transition from oil and natural gas to coal.

Economic competitiveness of an individual energy technology can be estimated generally in terms of energy production cost. However, for such technologies as producing several energy carriers with different energy market, proper estimation is difficult. Here the marginal cost, or shadow price, given to each energy carriers in the optimized energy system is utilized as an alternative measure. The marginal costs of representative energy carriers in the analytical case of low demand/high price-minimum P are compared in Fig. 13-b).

According to the results, high temperature nuclear heat is economically produced by VHTR with sufficiently low cost compared with oil products. Reducing gas produced from high temperature nuclear heat becomes more attractive than coke after the year 2015. The marginal cost of hydrogen in the transformation sector almost reaches those of oil products in the end of the time horizon indicating the possibility of having competitiveness early after the year 2020. The marginal cost of hydrogen in the end-use sector is much higher than the above because of high delivery cost per energy quantity. Heavy liquids from coal can compete with oil products almost from the date when the technology is available. While, synthetic gas from coal steam-gasification can compete with LPG only from the year 2015.

The input-output analysis by E-I/O(TRANS) has been made using the information on inputs, investments, and imports of energy sectors and energy inputs to non-energy economic sectors all determined through optimization of energy systems. The input coefficients of energy sectors have been determined based on the annual O&M costs of energy technologies and the data on industrial disaggregation of the cost for each technology. The requirements for investment goods and services by energy sectors have been determined similarly. Relative input shares of four energy sectors, i.e. coal, oil, electricity, and gas, in each of non-energy economic sectors have been determined based on the fuel mix in final energy consumption. These data have been forcibly incorporated into the framework of input-output analysis in I/O(TRANS) and simulation studies on inter-industrial transactions have been carried out for the analytical cases of high demand/high price-minimum P and high demand/low price-minimum P.

Domestic production of energy sectors shared about 4.5% of total domestic production in the year 1980. This is equivalent to 10% of gross domenstic products in the same year. According to the results of analysis, corresponding figures change to 6.4 % and 14 %, respectively, in the year 2020. While, the share of energy inputs in total factor inputs to all industries changes from 8.3% in the year 1980 to 12.3 % in the year 2020. The change in input structure is shown in Fig. 14.

Energy is no more than a sort of raw materials from the standpoint of national economy. Domestic production of energy industry is smaller even compared with food industry. Nevertheless, energy has a specific economic significance, mainly because almost all industries including those in the tertiary sector require it more or less for their activity. Fig. 14 indicates the possibility that the situation becomes more prominent in future.

Another point to be noted for Fig. 14 is the change in input strcutures of energy industries. The current role of energy industries as a whole is, roughly speaking, mainly to import oil, an energy carrier of already high value, and to provide it to end-users adding small value through refinery, storage, and delivery. However in future energy systems, as observed before, high value-added energy carriers must be produced from low grade resources by employing large-scale facilities. Then, the share of value added in total factor inputs increases necessarily. This change is large in coal industry as shown in Fig. 14.

In the optimization studies by MARKAL, market competition of energy technologies has been analyzed based on their costs presented in real term. However, competition of energy technologies is naturally made at any time based on their nominal costs determined by current prices of goods and services. While, the share of individual goods and serivces required for construction, operation, and maintenance is different among technologies. Therefore, marketability of a future technology would be more properly analyzed by using the costs reflecting possible changes in prices of goods and services.

The evolution of technology costs under the structural changes in economy has been analyzed as the first step for the above approach. Fig. 15 shows the results on representative technologies. The investment costs of electicity generation technologies are almost constant during 1980s, because output prices of general machinery and electric machinery industries decreases with large technology progresses. After the year 2000, increases of costs for LWR and coal-fired electric are large because of their heavy dependency on building industry. While, those for oil-fired electric are small because of depending more on machinery industry. These results indicate that, if past trend of technology progress in each industry is kept to some extent toward future, more than negligible changes will be given to relative costs between energy technologies.

In summary, reflecting the structural changes in energy supply and demand, the share of investment and O&M costs in total energy system cost increases significantly in future. From the viewpoint of market competition of energy technologies, enough marketability of high temperature nuclear heat and favorable possibility of reducing gas and synthetic fuels is indicated. The economic role of energy industry is expected to change in quality, not in quantity, so as to produce high value-added energy products from cheap and low grade resources by employing advanced technologies and capital. Finally, future technology progress in each industry would possibly change relative costs of energy technologies, and hence it is desired to make further analysis on this point.

6.3 Environment

Emission data described in chapter 5.4 are used for input data of element technologies in MARKAL and emission control systems are integrated into the reference energy system. From the results in effluent minimization calculation on reference energy system without emission control system, future situations of emission release under control by energy system of itself are analyzed. While, future situations of emission release under control by energy system and installation of emission control equipments are analyzed from the results with the emission control system.

Analysis is made on the results of case studies in trade-off relationship between total system cost (P) and total amount of effluent (E) from energy system with and without emission control equipments, as shown in Table 7.[6] In these calculations, objective function fo is composed of P and E as follows: i.e.

$fo = P + Q(N)\{\Sigma\ q(i)Ei\},\ \Sigma Ei = E,$

where Q(N) is penalty of total amount of emission to total system cost, q(i) is the importance of emission kinds in optimization, and $Q(2) = 1.0$, $Q(4) = 3.0$, $Q(5) = 6.0$. The symbol P means the calculation case of $Q(N) = 0$, and QN means the calculation case of Q(N), and E means the calculation case of $P = 0$, and EP means the calculation case of $fo = P$ under the constraints of $E \leq (fo)_{p=o}$.

Fig. 16 shows yearly change in amounts of each emission in the case of a) without emission control technologies (case 1B-P/Q2/Q5/EP/E in Table 7), and b) with emission control technologies (case 50-P/Q2/Q4/EP in Table 7). From Fig. 16-a), it is observed that yearly change of SO_x emissions shows almost same trend in case Q2, Q5 and EP. They decrease until the year 1995 and increase after 1995. The reasons are i) SO_x emission from conversion and process technologies reduces until the year 1995, and ii) SO_x from conversion technologies increases after 1995.

Extreme reduction case of SO_x (1A-E) is also plotted in left hand side figure, and it shows that large difference exists in different importance case. The figures are obtained from NO_x suppressed case, however, NO_x emissions of case Q2, Q5, EP and E have same tendency because those are mainly caused by elimination in only process technologies.

The reasons why we can observe a peak value at the year 2000 in each amount of emissions in both standard case (50-P) and (1B-P), are caused by the amounts of oil and coal in primary energy supply. The growth of SO_x at 2000 depends upon large amount of introduction of geothermal power plant and on increase of coal utilization.

In extreme case, the amount of SO_x and NO_x emissions can be reduce to 7 and 11 % of the standard P case, respectively, but the amount of CO_2 cannot be eliminated less than 65 % of the standard P case. These results show that effective countermeasure could not be found out in this energy system for reduction of CO_2.

Cost throwing effects of emission control are large in the case SO_x, middle in the case NO_x, and small in the case CO_2. Total amount of SO_x, NO_x and CO_2 emission over the term per total control cost are 1.739 $Nm^3/\$$, 0.935 $Nm^3/\$$ and 0.105 t/\$ in (50-Q2) case, respectively. They are 0.723 $Nm^3/\$$, 0.600 $Nm^3/\$$, 0.0835 t/\$, in 50-Q4 case and 0.085 $Nm^3/\$$, 0.084 $Nm^3/\$$, 0.021 t/\$ in (50-EP) case.

Sources of residual emission in SO_x after the year 2000 in (50-EP) case are occupied to 70 % by the emission from geothermal power plant and residual emission from chemical industries, and occupied to 30 % by residual emission from other conversion and process technologies and demand devices. In the case of NO_x, large part of residual emission are caused by automobile and industries which use high temperature furnace.

Fig. 17 shows the composition of emissions a) in case (1A-P/E), b) in case (1B-P/E), and c) in case (1C-P/E), and all of these are cases of without emission control technologies. From these figures, we can observe that SO_x is eliminated easily by reductions in emission from conversion technologies and demand technologies, especially from geothermal power plant, space heating, and boilers and furnace. In the case of NO_x emission, large eliminations are found in emission from coal power plant, LNG power plant, furnace, and space heating.

Fig. 18 shows estimated trade-off curves between reduced rate of total amount of emission and increased rate of total system cost in main calculation case. In the case 1C, 10, and 50, the point Q2, Q4 or Q5 are also given. From this figure, following observations are obtained.

Comparing points (10-Q2), (10-Q4), (50-Q2), and (50-Q4), the effect of the control on the emission from demand devices is greater than the effect of the control on the emission from conversion and process technologies in future, and the difference of cost in both cases is not so large. Comparing the slope from (30-EP) to (40-EP) and from (40-EP) to (50-EP), the effect of controls on NO_x emission is larger than the effect of SO_x controls, while the cost of NO_x control is less than that of SO_x control in demand devices.

In the series of case (50), the effects of control are caused both by the structure change of energy system and by the adoption of emission control technologies. Detail inspection of the results in calculation case (50-EP) shows that the ratio between the former effect and the latter effect is 58/42 in total amount of emissions, 43/57 in the amount of SO_x emission, 30/70 in NO_x emission, and 93/7 in CO_2 emission, respectively.

From the comparison between the results of case (10) and case (50), it is said that the cost of introduction of control technologies is cheaper than the cost of the change of energy system. The cost of 1.0 % reduction in total amount of emission in the case of (Q2) point are 1.857×10^9 \$ in the case (10) and 0.179×10^9 \$ in the case (50), and the difference reached almost one decade.

In the case without control technologies, it is observed that total amount of emission becomes large in the order of case (1C), (1B), and (1A). Total amount of emissions in case (1B-EP) is about twice that of case (10-EP), and this reason is that emission from conversion technologies increase by the NO_x suppression. From detail examination on point (1C-EP) shows that total amount of emission reaches 2.25 times that of case (10-EP) in the amount of SO_x emission and 1.13 times in NO_x emission.

Fig. 19 shows some of the information on the change in total energy system where emissions are controled by various methods; i.e. a) shows the situations of primary energy supply in (1C-Q5), (10-EP), (10-P), and (50-Q4) case. b) shows the transition of final energy demands in each case. c) shows the changes of composition in electricity generation in each case.

In the case where emission control is depended upon the fuel subsitution and on structure change of energy system (1C-Q5, 10-EP case) the amount of primary energy increases. This phenomena is caused by the reason that renewable, nuclear, and natural gas are used a lot, and that oil is transferred in cleaner energy through oil refineries and other suitable processes. In the case where emission control technologies are added to energy system (50-Q2), almost same effects as upper case are obtained by introducing equipments of emission control, and almost same patterns of primary energy supply as in case (10-P) are maintained.

There is no figure of case (50-EP), however, the pattern of primary energy supply in case (50-EP) becomes almost same as that of case (10-EP), and the amount of primary energy increases. This means that the substitution and transformation of fuel are advanced in the case (50-EP), and that large amounts of fuel oil condensed by sulfur and nitrogen are thrown away after the oil-refinery, and that these method of emission control should be avoided in future from economical view point.

However, it is clear that the countermeasures of SO_X, NO_X, CO_2 emission control are promoted by the introduction of control equipments at first, and by fuel substitution at 2nd, and by fuel transformation at last from point of economical view. In fuel transformation fields, oil-refinery goes ahead than introduction of such new technologies as new-liquid fuel utilizing nuclear heat.

In Fig. 19-b), fuel substitutions are promoted early in final energy used in the demand devices, especially in the field of fossil fuels. Gas trespasses the field of coal and oil direct utilization. The reason why the shares of electricity and coal are limitted in final energy demand is that the energy mix in demand devices has rather hard structure for choice of fuel mix.

From Fig. 19-c), it is noticed that the nuclear share is large in all cases and it is about 56, 57 % at the year 2020 in case of (50-Q2) and (50-Q4) respectively, however, it reaches 65 % in the case of (10-EP). Coal fired power plants are reduced and gas fired power plants increase in proportion to the promotion of fuel substitution.

From the above results, we summarize easily that we can not avoid large amount of emission from energy system in future under the simple consideration of cost-minimum, and easily imagine that nor avoid even in the case of security minimum, and easily derive the conclusion that amounts of SO_X and NO_X could be reduced by introdusing emission control technologies within rather small amount of cost in future.

However, it is important to notice that figures in this section show not cumulative but annual amount of emission not existing in the air but released from element technologies, and that the reduction of NO_X seems expensive and the reduction of CO_2 seems difficult, and that large amount of reduction in EP case depends on uneconomical fuel substitutions.

Details of the results from analysis on the relationship between the effect on emission release and nuclear heat utilization technologies were described in chapter 6-4), however, one of those conclusion is that constraints and bounds on the introduction of nuclear heat by VHTR could not permit the introduction and activities of CO_2 recycle technologies and new technologies for clean energy, and that only uneconomical fuel substitution by oil is left for the system to take under the hard suppression on emissions.

For checking and proving for this conclusion described in the above, special optimization calculation is carried out in the case (50-EP), where constraints and bounds on the introduction of VHTR are set free and the amounts of oil import are bounded under the values that are 10 % higher than that of (50-Q4) case. In the results of this optimization case, patterns of primary energy supply are almost same as that of case (50-Q4), and installed capacity of VHTR becomes 30 GWt at the year 2020 and can maintain same value of total amount of emissions.

These results can make clear that the effects of VHTR and nuclear heat utilization technologies are enormously large and could be expected after the year 2020, when the importance of VHTR is recognized and large commercial introduction could be permitted by public.

6.4 Technologies

In this section the results are discussed on implementation of the technologies, especially of new technologies included in the reference energy system. The viewpoint of the analysis is placed especially on the following three points: (a) By which technologies future trend of electrification is promoted. (b) Which utilization technologies will be introduced to the process heat applications aiming at effective utilization of energy. (c) Which technologies can contribute to promote the transition from scarce and expensive oil and natural gas to coal.

The results obtained in the analysis on the trade-off relationships between total system cost and security of supply are described first. Fig. 20 shows the introduction dates of new technologies in the low demand/ high price cases. While, the results on implementation of new technologies for high temperature heat utilization and for coal conversion are shown in Fig. 21.

Nuclear power takes a central role in future electricity generation, and the LWR shares most of its capacity until the year 2020. The HTGR and the FBR have enough competitiveness at this time period, however, the contribution is still small. Among technologies for other base-load and middle-load electricity generation, advanced coal-fired, LNG combined cycle and geothermal electric make a considerable contribution, and have sufficient economic performances in comparison with conventional fossil technologies in near future.

Pumped storage continues to take a major role as a peak-load technology under the support of gas turbines and a battery storage. Renewable technologies, such as solar photovoltaic and wave, have possibility of getting marketability after around the year 2000 depending on the future prices of fossil fuels. Cogeneration technologies using fossil fuels as well as the LWR have enough possibility to compete with dedicated technologies for electric power generation and low temperature heat production.

The VHTR is introduced to its upper limit from the year 2010, and this result indicates sufficient marketability of high temperature nuclear heat in comparison with conventional fossil heat sources in future years. The utilization of the high temperature nuclear heat is made flexibly depending on the prices between coal and oil, or natural gas.

In the standard case (P case), the high temperature nuclear heat is utilized mainly for methane reforming process and reducing gas production, while it is utilized mainly for thermochemical heat pipe and high temperature electrolysis in the case giving a premium to the prices of oil and natural gas (QP case).

Methane steam reforming is disadvantageous in the case QP, because the main source of methane utilized there is natural gas. Reducing gas production is also not implemented in the case QP, because reducing gas substitutes coke, and not oil products nor natural gas.

The hydrogen produced by nuclear heat is used in coal hydro-gasification and methanol synthesis to produce substitutes of natural gas and oil, respectively. On the other hand the CO gas is directed to the CO gas-turbine combined cycle and to the methanol synthesis process. The thermochemical heat pipe supplies steam of medium temperature to industrial boilers as substitutes of fossil fuels, and contributes to reduce fuel oil.

The technologies which primarily contribute to the transition from oil and natural gas to coal are coal liquefaction and gasification. Among coal liquefaction technologies, heavy liquids production at oversea plants is most promissing. It is introduced from the year 2010 in the P case, while from 1995 in the QP case. Light liquids production at oversea plants and the domestic F-T liquefaction are introduced later on. On the other hand coal steam-gasification and hydro-gasification technologies are introduced from the year 2005 or 2015 in the eariest case, though the dates largely depends on the relative prices between coal and oil, or natural gas.

The new technologies in the end-use sector also contribute much to effective utilization of energy and reducing the dependency on oil products. Heat pumps are utilized for residential space heating and air conditioning, and are expected to be promising technologies for effective utilization of energy. In the transportation sector, electric cars are introduced from the year 2000, and further methanol cars have competitiveness from the year 2005. Nuclear ships, introduced to the upper bounds in all cases, contribute to the reduction of fuel oil consumed for international freight transportation.

The above results are summarized as follows: (a) Future trend of electrification is prmoted by nuclear technologies which play a central role in electricity generation. (b) High temperature nuclear heat has sufficient competitiveness with conventional fossil heat sources. (c) In the transition from oil and natural gas to coal, coal conversion technologies play an important role. In particular, the contributions by heavy liquids production at abroad and coal steam-gasification are large.

The transition of element technologies in the analysis on the trade-off relationships between total system cost and total amount of emission can be also observed in Fig. 19 on which explanations are already described in section 6-3). Until the 50-Q4 point where uneconomical fuel transformation has not yet started largely, element technologies related to oil and oil products are reduced, and installed capacities in the field of nuclear, renewable and natural gas and coal are increased.

The different observation points from the results of cost/security trade-off analysis are,: i) fuel transformation technologies using coal increase during the term when fuel substitution is main method of control (Q4), but decrease in the case fuel transformation began to control (1C-Q5, 10-EP, 50-EP). ii) LNG technologies are promoted rapidly in all cases. iii) the pattern in the introduction of nuclear heat utilization technologies has complex characteristics in the environmental analysis.

Fig. 22 shows installed capacities of VHTR and nuclear heat utilization technologies in the case of P, Q2, Q4, EP from the year 2000 to 2020. a) shows the comparison between NO_X control case (1B) and SO_X control case (1A). b) shows the comparison between with control technology case (50) and without control technology case (10).

The differences between the results of case 10 and case 50 are large in the capacity of reformer in Q4 case, thermochemical hydrogen production (UT-3) in Q2 and Q4 case, thermochemical heat pipe in Q2 case, methanol plant in Q4 case, and reducing-gas plant in EP case. The reason is mainly due to the upper bounds of VHTR installation. Considering the cost in P, Q2, and EP case, large part of high temperature nuclear heat is consumed in the production of reducing gas, and the rest is used for the production of hydrogen or methanol through the reformer, or used for hydrogen production by UT-3. These selection is depended on competitive situation of cost and amount of emission, and former two plants are selected in the case 10 and UT-3 is selected in the case 50.

While, as the characteristics of emission control is considered much important than cost characteristics in the EP case, capacities of reducing gas production plant become nearly zero and are declining in case 10. Nuclear heat is utilized in the reformer and produces high temperature steam and synthesized natural gas. The steam is utilized for generating clean energy, electricity. SNG is utilized for producing mainly hydrogen or consumer gas.

There is no selection for production of methanol nor production of gasoline by using CO, H_2, CO_2 produced in the process mentioned above, because the demands of methanol are limitted and are fulfilled by alcohol produced by renewable energy. In the case of gasoline, similar observation is obtained; i.e. plenty of oil can produce gasoline easily in EP case.

Even in the emission-minimum case, CO_2 recycle system considered in reference energy system can not be adopted, because the system needs plenty of high temperature nuclear heat, hydrogen, and electricity.

7. Concluding Remarks

The results of this system analysis are not based on the descriptive methodologies, but derived from the analysis on optimal solutions based on normative methodologies, therefore, the results are not prospects, nor forcast, nor projection of future, but the solution of optimization under the object function of total cost minimum, security minimum, and total amount of emission minimum, and are role of partial solution within total solution. At the same time, the results are also derived from the discussion based on the principles for what and how the energy system should be in future of Japan.

However, uncertainties in society, economy, and environment which are surrounding energy systems are not neglected in this analysis. Normative analysis has been done within scenario regions which were created and analyzed sufficiently by descriptive methodologies. Therefore, the results of this system analysis have continuities from now, and are not emotional solutions of optimization problems but trustful solutions which have sufficient realities.

As we have done many simulation studies based on trial and error sequencies in setting exogenous variables and in generating scenarios, and as we have done many case studies and sensitivity analysis by simulation studies in structural analysis, the results obtained from this system analysis have sufficient robustness and resilience for future uncertainties.

As far as the characterization of element technologies are concerned, we adopt central values in estimated range, however, these are owing to future progress in R&D of each technologies. More detail assessment on technical and economic characteristics of element technologies should be continued.

We have completely finished four study subjects mentioned in chapter 2, the answers for principle view points for future energy system are mentioned in the results of analysis in chapter 6. Three kinds of performance indices, total system cost and amount of total effluent and amount of import oil and oil products and LNG, are programmed into the objective function in the form of two combination, therefore, detail observation can look out small difference within the results obtained from different objective functions.

Nuclear plays important role in every scenario case under every kind gas production plant become nearly zero and are declining in case 10. Nuclear heat is utilized in the reformer and produces high temperature steam and synthesized natural gas. The steam is utilized for generating clean energy, electricity. SNG is utilized for producing mainly hydrogen or consumer gas.

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Nuclear plays important role in every scenario case under every kind of objective functions described above and has a large share in future energy supply system of Japan. Especially, VHTR is introduced till the upper bounds after the year 2010. As the production of nuclear heat is constrained by the upper bounds, adoption of nuclear heat utilization technologies is restricted partially.

In security case, oil and oil products are substituted by coal and renewable energy, and LNG is substituted by SNG from coal. In emission minimum case, utilizations of coal are suppressed except the use for SNG which compensate insufficiency of LNG. In the field of electricity generation, advanced coal power plants are adopted easily in former case, however, they are standing by for peak load and do not generate electricity in the latter case.

Renewable energy has also a certain role for future in both objective functions. Hydro-power, renewable, and geothermal power plant are adopted. Detail review of element technologies are mentioned in 6-4).

From the results of this analysis, some observations on the characteristics of objective functions are obtained. Minimization of total system cost effects homogeneously to the selection of all element technologies, on the contrary, minimization of security has larger effects to the substitution of fuel mix than to the selection of element technologies. While, minimization of total amount of emission has large effects to the setting of fuel mix in demand devices because of its characteristics in fuel substitution and fuel transformation.

We can say that emission problems largely depend upon the movement of main energy carriers used for final energy consumptions. For attempt to the future expansion in the role of VHTR from environmental view points, it seems necessary for VHTR to adapt for energy form requested by demand side. Multi purpose utilization of high temperature heat from VHTR should be considered including the R&D on new energy carriers.

Many problems and subjects for further study have been also extracted from this analysis. In the view of energy demand and supply, more detail examination on constraints in primary energy supply could produce fruitful results. In the view of economics, analysis on the feedback effects from structural analysis to macro economy will be necessary. In the view of environment, including the technologies of desulfurization and de-nitrification in fuel is necessary at first.

Within the subjects for further studies, the importance of technical assessment is recognized in every case study. We cannot ignore feedback effects to the competitive conditions by the changes in economic characteristics of element technologies caused by structural changes in future. We should compensate these insufficiencies by more detail technical assessment of each element technologies.

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Table 1 Outline of Economic Life in the Macro Economic Scenarios

Scenario / Case / Item / Year	1980	Scenario α				Scenario β			
		1990	2000	2010	2030	1990	2000	2010	2030
Gross Domestic Product (10^{12} YEN, 1975 const.)	192	268	355	431	527	250	318	364	422
Real growth rate (%/y)	9.7	2.9	2.3	1.6	0.4	2.4	1.4	1.2	0.7
Indexes of industrial Production (1975=100)	143	193	254	298	330	182	234	261	281
Wholesale price index (1975=100)	132	152	190	238	359	159	206	248	306
Consumption tendency $\left(\frac{\text{Private consumption}}{\text{national income}}\right)$%	62	41	31	24	20	41	31	26	24
Tax burden (Tax / national income)%	17	19	20	20	28	19	21	22	36
Unemployment rate	2.3	2.2	2.5	2.7	2.5	2.0	2.1	2.4	2.5
Compensation of employees (10^{12} YEN, 1975 const.)	125	227	358	497	770	230	364	469	489
Money Supply balance (10^{12} YEN, 1975 const.)	201	352	553	809	1469	350	544	743	1023

Table 2 Main Indices of Energy-Economy Scenarios

Item / Case / year	10 years Average Growth Rate of GNE		Final Energy Demand Scenarios PJ / year		Usefull Energy Demand Scenarios PJ / year	
	Low *	High *	Low *	High *	Low	High
1980	2.7	3.4	10880		5544	
1990	2.4	2.9	11640	12035	6495	6690
2000	1.3	2.0	13400	13640	7970	8288
2010	1.0	1.5	14000	15000	8637	9357
2020			14650	16325	9304	10426

* High and Low case correspond to α and β case in the analysis of scenario generation.

Table 3 Main Characteristics of Representative Technologies

Technology		Technical Data			Cost Data		
		Lifetime (Year)	Availability (%)	Efficiency (%)	Inv. Cost $/*1	Fix. Cost $/*1/Yr	Var. Cost $/GJ
Conversion Technology							
E01	Conv. Coal-Fired	20	70	35.2	901.6	38.0	0.51
E06	Adv. Coal-Fired	20	70	44.0-48.0	919.6	40.0	0.80
E13	Oil-Fired	20	70	39.1	522.9	22.4	0.16
E21	LWR	30	70	33.7	1422.	81.6	0.67
E26	LMFBR	30	70	40.3	1849.	106.0	*3
E31	Hydroelectric	50	45	——	2378.2	83.3	*3
E32	Geo-electric	20	80	——	1812.	72.0	0.08
E4B	Solar Photovol.	20	50	——	3056.2 -1439.6	2.3	*3
E9A	He Gas Turbine	30	70	43.0	299.1	14.8	0.38
E9C	CO Gas C.C.	30	80	60.0	688.	40.5	0.18
Process Technology							
S01	Coal Hydrogas.	20	90	88.8	3.19	0.14	0.06
S02	Char Steam-gas	20	90	91.9	5.54	0.29	0.14
S03	Coal Steam-gas	20	90	86.6	6.58	0.41	0.12
S0E	Coal Liq. (Light)	20	90	65.0	35.57 -23.72	1.18 -0.59	0.37 -0.19
S0F	Coal Liq. (F-T)	20	90	63.0	16.40	0.55	0.17
S0G	Coal Liq. (Heavy)	20	90	70.3	28.90 -19.26	0.91 -0.46	0.29 -0.15
S91	Steam Reform	20	90	97.0	1.77	0.08	0.04
S93	Thermochem. Pipeline	20	90	88.6	7.61	0.50	0.18
S97	Thermochem. H_2	20	90	100 *2	1.51	0.11	0.06
S98	Coal to Red. Gas	20	90	70.9	3.09	0.32	0.07
S9C	CO-H_2 Sep.	20	90	90.3	3.62	0.17	0.32
S9D	H.T. Eloctrolysis	20	90	96.9	12.03	0.64	1.16
S9K	Methanol Syn.	20	90	94.6	1.43	0.08	0.03
S9M	Gasoline Syn.	20	90	82.9	2.95	0.20	0.09

*1. capacity unit of technologies i.e. kW for conversion technologies
GJ/y for other technologies

*2. assumed full use of recovery heat

*3. included in fixed cost

Table 4 Emission Coefficients of Representative Technologies

at 1980

Technology			SO_x $10^6\ Nm^3/PJ$	NO_x $10^6\ Nm^3/PJ$	CO_2 $10^3\ t/PJ$
Conversion Technology					
	E01	Conv. Coal-Fired	0.026	0.108	87.6
	E06	Adv. Coal-Fired	0.026	0.108	87.6
	E13	Oil - Fired	0.092	0.198	72.2
	E82	Gas - Fired	0.001	0.019	50.6
	E32	Geo - electric	0.670	—	—
	E81	Conv. Gas Turbine	0.001	0.071	94.7
	E80	LNG Complex	0.001	0.160	50.6
	E61	Coal Cogeneration	0.026	0.010	87.6
Process Technology					
	S01	Coal Hydrogas	0.002	0.005	—
	S02	Char Steam-gass	0.005	0.013	—
	S03	Coal Steam-gas	0.005	0.014	—
	SOE	Coal Liq. (Light)	0.007	0.011	—
	SOF	Coal Liq. (F-T)	0.010	0.011	30.7
	SOG	Coal Liq. (Heavy)	0.003	0.008	—
	S98	Coal to Red. Gas	0.003	—	—
	S06	Coke furnace	0.006	0.017	17.5
Demand Technology					
Industry	IDH	Paper & pulp Boiler	0.291	0.096	133.5
	IGH	Chemical Furnace	0.574	0.148	185.7
	IHJ	Chemical Boiler COM	0.268	0.169	144.5
	IHK	Chemical Boiler COD	0.198	0.245	158.5
	IOL	Iron & Steel Reduction	0.068	0.118	125.4
Residential & Commercial	R19	Space Heating	0.003	0.082	173.9
	R2F	Walter Heating(office)	0.006	0.036	98.8
	RBK	Walter Heating(House)	0.227	0.235	152.1
	RD9	Air Conditioning	0.003	0.065	225.9
Transport	T1G	Railway	0.309	1.847	417.5
	T2C	Automobile	0.023	0.068	382.2
	T3G	Truck	0.222	0.242	299.7
	TAE	Air	0.018	0.029	307.4

Table 5-a) SOx Reduction Equipments

SO_x ppm	Equipment Scale 1)	Super Large	Large	Middle	Small
2200	70	SHA	—	—	—
	80	SHE	—	—	—
	90	—	—	—	—
1500	70	SHB	—	SMB	SSB
	80	—	—	SMF	SSF
	90	—	—	SMJ	SSJ
1000	70	SHC	—	SMC	SSC
	80	—	—	SMG	SSG
	90	—	—	SMK	SSK
450	70	—	—	SMD	SSD
	80	—	—	SMH	SSH
	90	—	—	SML	SSL
—	75.6	—	—	—	SSX 2)
	36.6	—	—	—	SSY
	93.5	—	—	—	SSZ

1) Desulfurization Rate (%)

2) Residential & Transport

Table 5-b) NOx Reduction Equipments

NO_x ppm	Equipment Scale SO_x ppm	Super Large	Large	Middle	Small
400	500	S8A	S8B	S8C	S8D
200	1500	S8E	S8F	S8G	S8H
	100	S8I	S8J	S8K	S8L
100	100	S8M S81	S8N	S8O	S8P
	0	S8Q	S8R	S8S	S8T
50	0	S82 1) S83	—	—	—
—	0	—	—	—	S85 2) S86 S87 S88

1) 2nd Stage Reduction at Severe Operation

2) Residential & Transport

Table 5-c) Technical and Cost Data of SOx Reduction Equipments

Equipments	SHA	SHC	SMF	SMC	SSL	SSX
Capacity 10^3 kW	2000	2000	220	220	37.5	—
Effluent Gas $10^3 Nm^3/H$	5800	5800	620	620	100	—
Inlet SO_x ppm	2200	1000	1500	1000	450	—
Outlet SO_x ppm	660	300	300	300	45	—
Desulfurization Rate %	70	70	80	70	90	75.6
Annual SOx Emmission $10^6 Nm^3$	111.778	50.808	8.147	5.431	0.394	—
Annual Capital Cost 10^6 $	141.6	141.6	22.89	22.00	4.632	—
Capital Cost $/$Nm^3$-$SO_x$/y	1.267	2.787	2.809	4.051	11.754	1.2305
Fixed O & M Cost $/$Nm^3$-$SO_x$/y	0.0529	0.1160	0.1173	0.1623	0.4701	0.2849
Variable O & M Cost $/$Nm^3$-$SO_x$/y	0.0838	0.1411	0.1230	0.1411	0.1985	0.2752
Electricity PJ/$10^3 Nm^3$-SO_x	11.28	16.54	25.54	25.54	60.00	0

Table 5-d) Technical and Cost Data of NOx Reduction Equipments

Equipments	S8A	S8F	S8K	S8T	S82	S85
Capacity 10^3 kW	700	88	35	47	700	—
Effluent Gas $10^3 Nm^3/H$	2300	280	100	15	2000	—
Inlet NO_x ppm	400	200	200	100	50	—
Outlet NO_x ppm	80	40	40	20	10	—
Denitration Rate %	80	80	80	80	80	80
Annual NOx Emmission $10^6 Nm^3$	8.059	0.491	0.175	0.0131	0.876	—
Annual Capital Cost 10^6 $	24.48	3.445	1.896	0.321	7.498	—
Capital Cost $/$Nm^3$-$NO_x$/y	3.037	7.015	10.824	24.476	8.559	7.680
Fixed O & M Cost $/$Nm^3$-$NO_x$/y	1.143	1.435	1.530	5.084	0.851	2.281
Variable O & M Cost $/$Nm^3$-$NO_x$/y	0.398	0.703	1.139	2.660	1.013	0.864
Electricity PJ/$10^3 Nm^3$-NO_x	4.11	8.47	9.44	16.79	37.79	0

Table 6 Main Indices of the Results in Trade-off Analysis

Scenario			Total System Cost($10^{12}\$$)	Security (EJ)	Primary Energy Cumulative Value (EJ)						
						Import			Domestic		
Demand	Price	Object F.			Total**	LIQ	SOL	GAS	NUC*	FOS.	REN
High	High	P	2.503	382.1	907.6	322.3	229.9	70.1	482.0	36.8	86.0
		QP	2.553	316.6	910.4	277.5	274.7	56.5	475.8	36.8	100.5
	Low	P	2.382	455.7	879.4	387.3	138.2	85.9	481.9	36.8	69.1
		QP	2.455	320.1	910.0	279.4	274.1	58.3	477.2	36.8	97.1
Low	High	P	2.391	373.1	853.0	312.4	224.6	64.9	404.5	36.8	76.8
		QP	2.429	317.4	856.0	274.4	255.3	58.8	397.5	36.8	91.8
	Low	P	2.276	443.2	827.3	385.1	137.9	72.4	404.3	36.8	57.8
		QP	2.336	319.8	855.5	274.9	255.3	60.9	398.1	36.8	88.9
Reference (Ultra - high)	High	P	2.814	451.5	1003.8	379.8	251.6	85.0	482.0	36.8	88.2
		QP	2.856	397.9	999.2	322.7	277.1	96.1	475.7	36.8	102.2
	Low	P	2.674	492.9	987.6	409.1	198.1	104.4	482.4	36.8	76.8
		QP	2.737	399.5	999.8	326.2	277.1	93.9	476.3	36.8	101.5

* unit of nuclear is 10^3 ton

** nuclear are counted for by fossile equivalent

Table 7 Case Studies of Environmental Analysis by MARKAL

Contents / Case NO.		Importance of each Emission			Emissions controlled by Control Tech.			Subjects of Analysis
		SO_X	NO_X	CO_2	CON	PRC	DMD	
1 A	Without Control Technology	100	1.0	0.001	—	—	—	Emission Control by Fuel Substitution Fuel Conversion New Technology
1 B		1.0	100	0.001	—	—	—	
1 C		0	0	1.0	—	—	—	
10	Normal Case	1.0	1.0	0.001	—	—	—	
20	With Control Technology	1.0	1.0	0.001	SO_X	SO_X	—	Emission Control by Fuel Substitution Fuel Conversion New Technology and Control Technology
30		1.0	1.0	0.001	SO_X, NO_X	SO_X, NO_X	—	
40		1.0	1.0	0.001	SO_X, NO_X	SO_X. NO_X	SO_X	
50		1.0	1.0	0.001	SO_X NO_X	SO_X. NO_X	SO_X, NO_X	

1) CON : Conversion Technologies. PRC : Process Technologies, DMD : Demand Device Tech.

2) In each case, P/Q(N)/EP/E points are calculated.

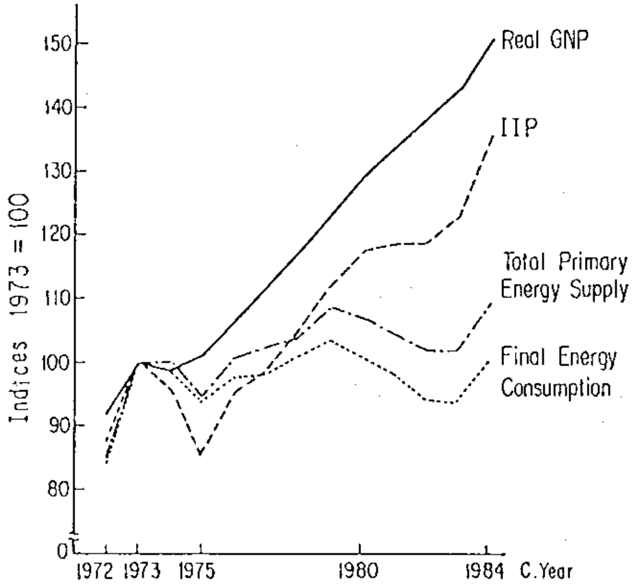


Fig. 1-a) Changes of GNP, IIP and Energy

(Source; 1) GNP; Economic Planning Agency 'Annual Report on National Accounts', 2) IIP; MITI, 'Annual Report on Index of Industrial Production' (1985), 'Report on Index of Industrial Production' (1983), 3) Energy; The Institute of Energy Economics, 'Energy Balances in Japan')

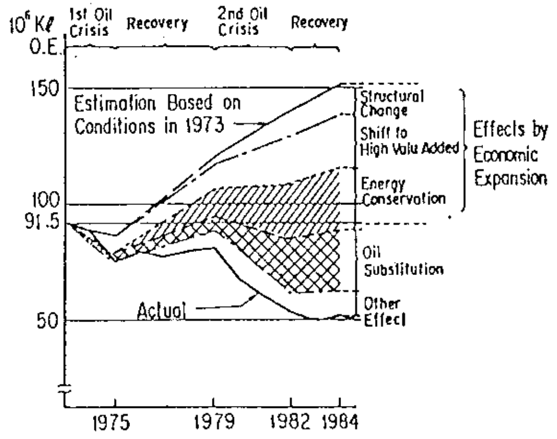


Fig. 1-b)

Cause Analysis of Changes for Oil Consumption in the Manufacturing

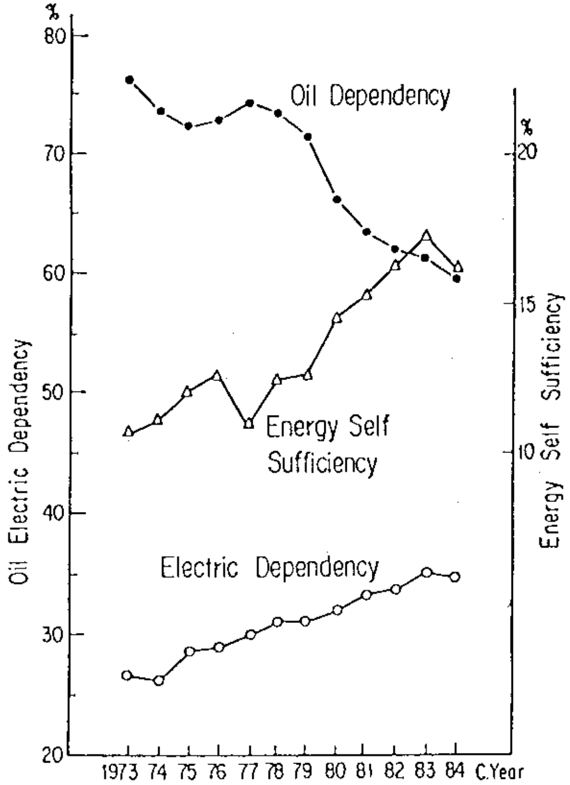
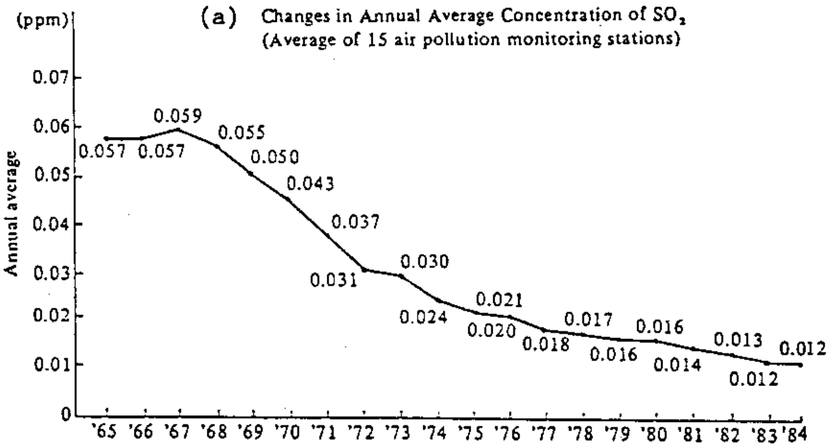


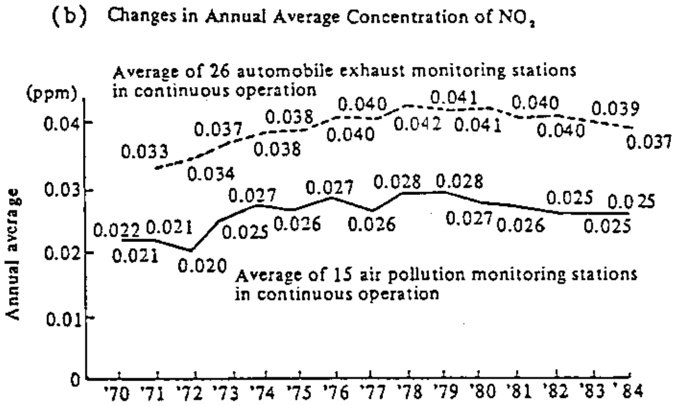
Fig. 1-c)

Changes of Oil, Electric Power Dependence Rate and Energy Self-sufficient Rate

(Source; The Institute of Energy Economics 'Energy Balances in Japan')


(a) Changes in Annual Average Concentration of SO_2
(Average of 15 air pollution monitoring stations)

Note: Annual average is the quotient of the sum of all one-hour values per year divided by the total measured hours.


(b) Changes in Annual Average Concentration of NO_2

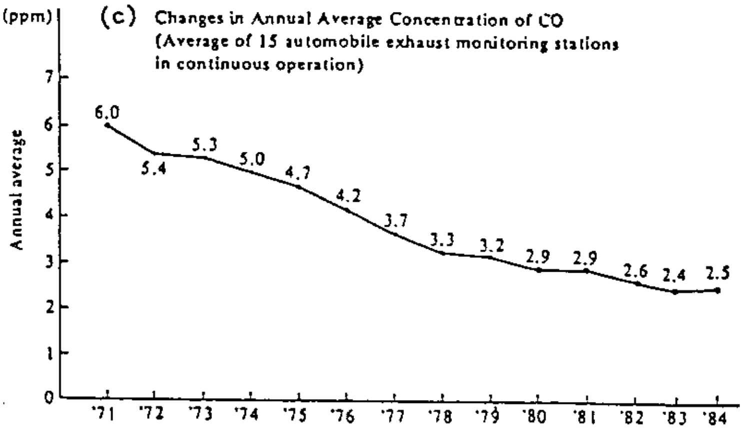
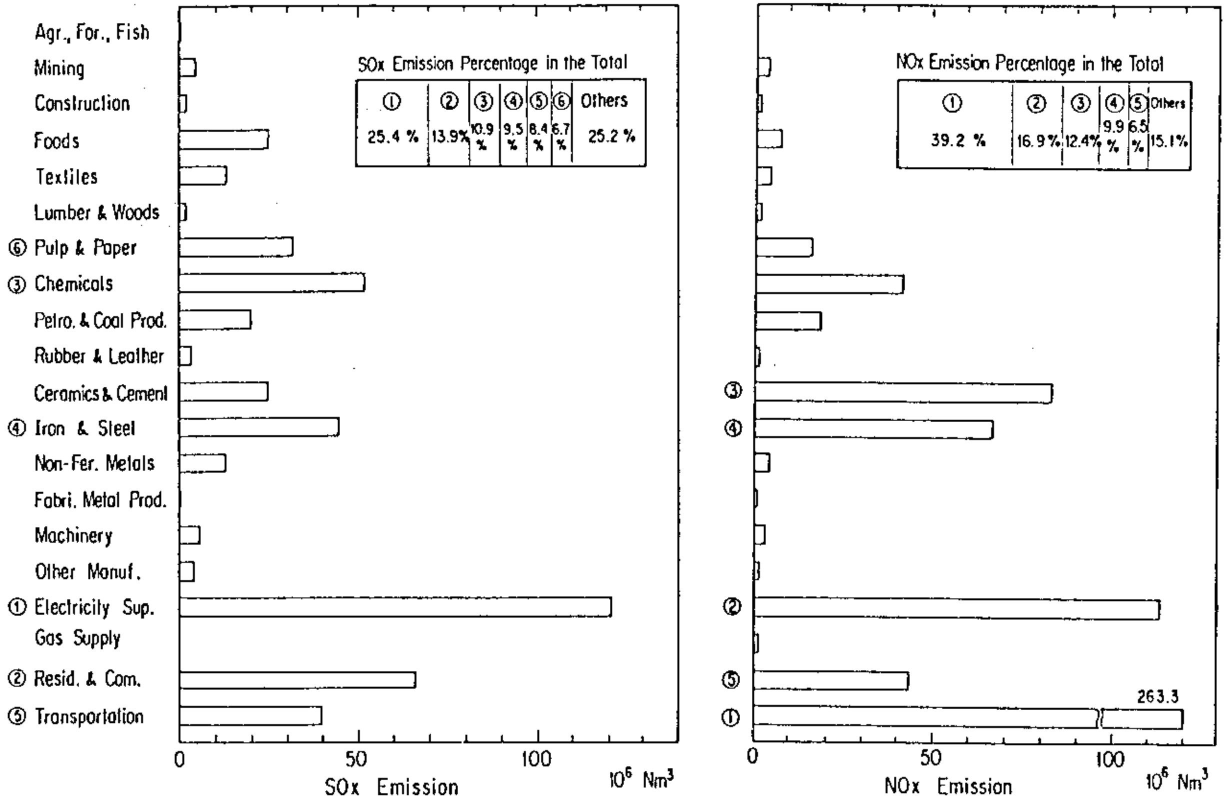

(c) Changes in Annual Average Concentration of CO
(Average of 15 automobile exhaust monitoring stations in continuous operation)

Fig. 1-d) Trends of Air Pollution

(Source: Environmental Agency ed., 'Quality of the Environment in Japan 1986.', Sansei Sougou Printing Co., Tokyo, 1986, p.p. 77-110. (English edition available)).

SOx. NOx Emission by Industry (at F.Y. of 1980)

(Source : MRI Report prepared for JAERI)



SOx. NOx Emission Unit by Industry
(at F.Y. of 1980)

(Source ; MRI Report prepared for JAERI)

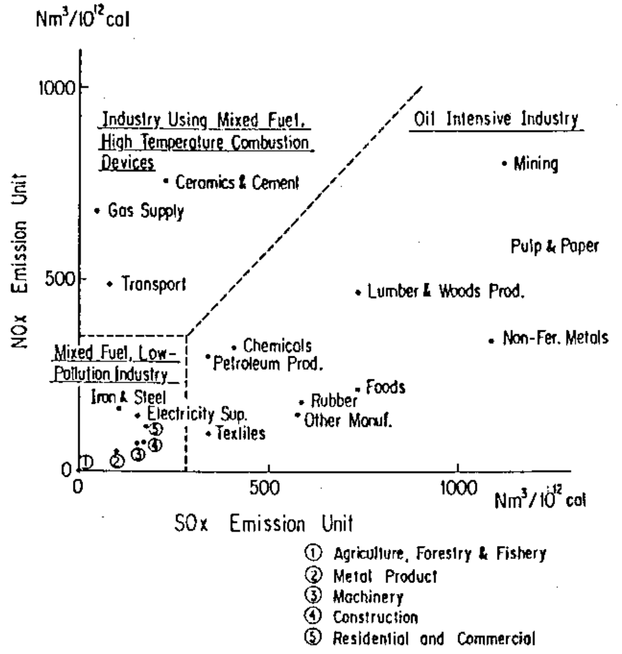


Fig. 1-e) SOx, NOx Emission Releases and their Emission Coefficients of each Industry

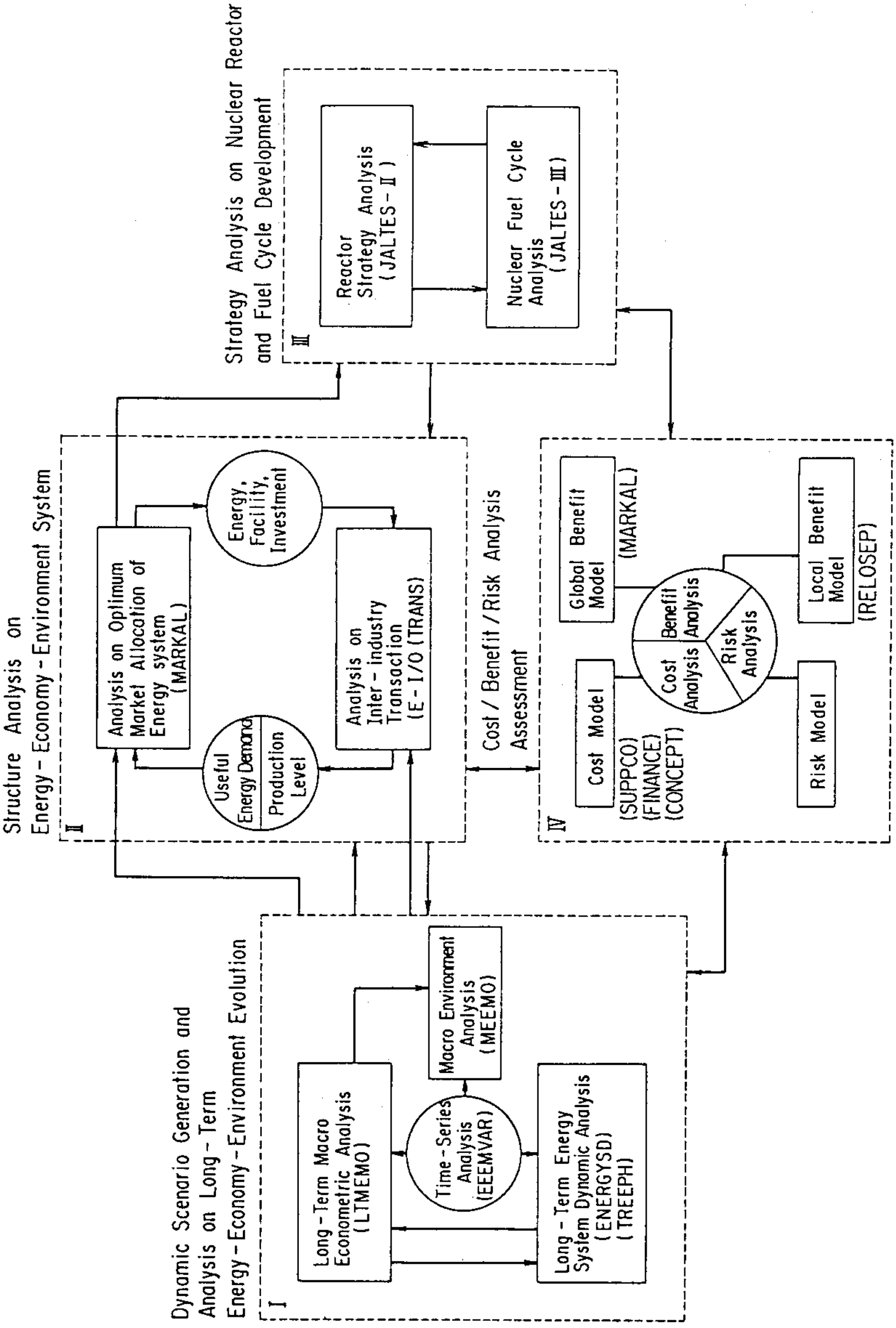


Fig. 2 Integrated Energy-Economy-Environment Model System

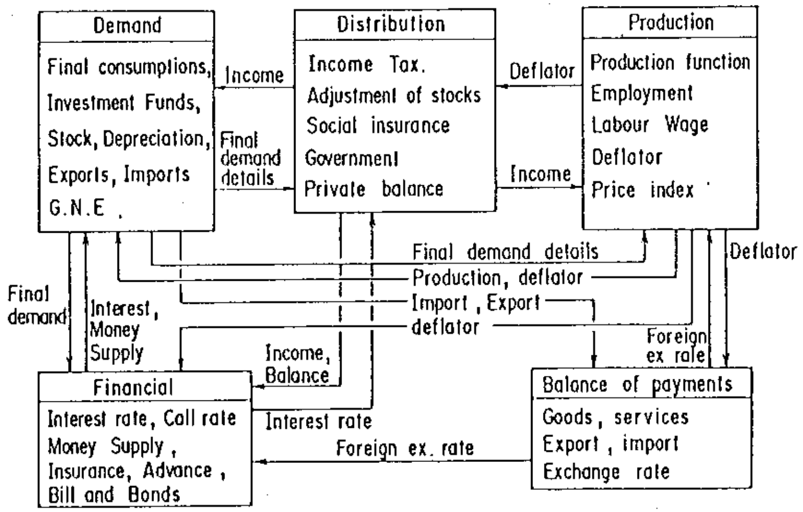


Fig. 3-a) Schematic Diagram of LTMEMO

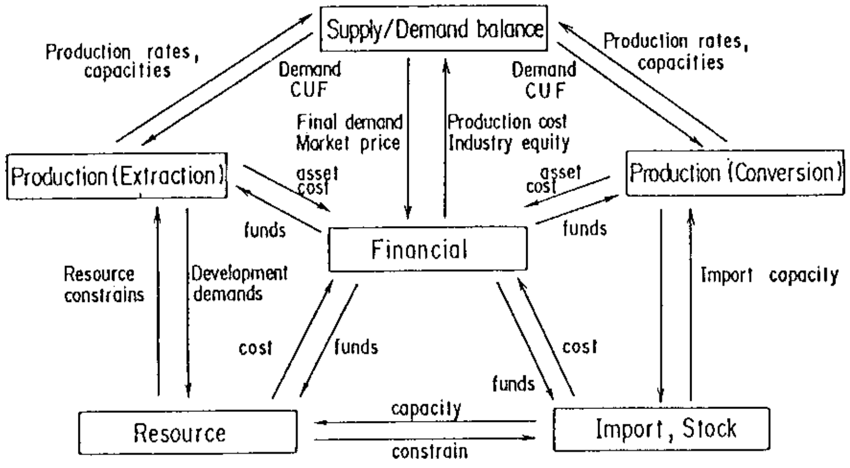


Fig. 3-b) Basic Structure of Macro Energy SD Model

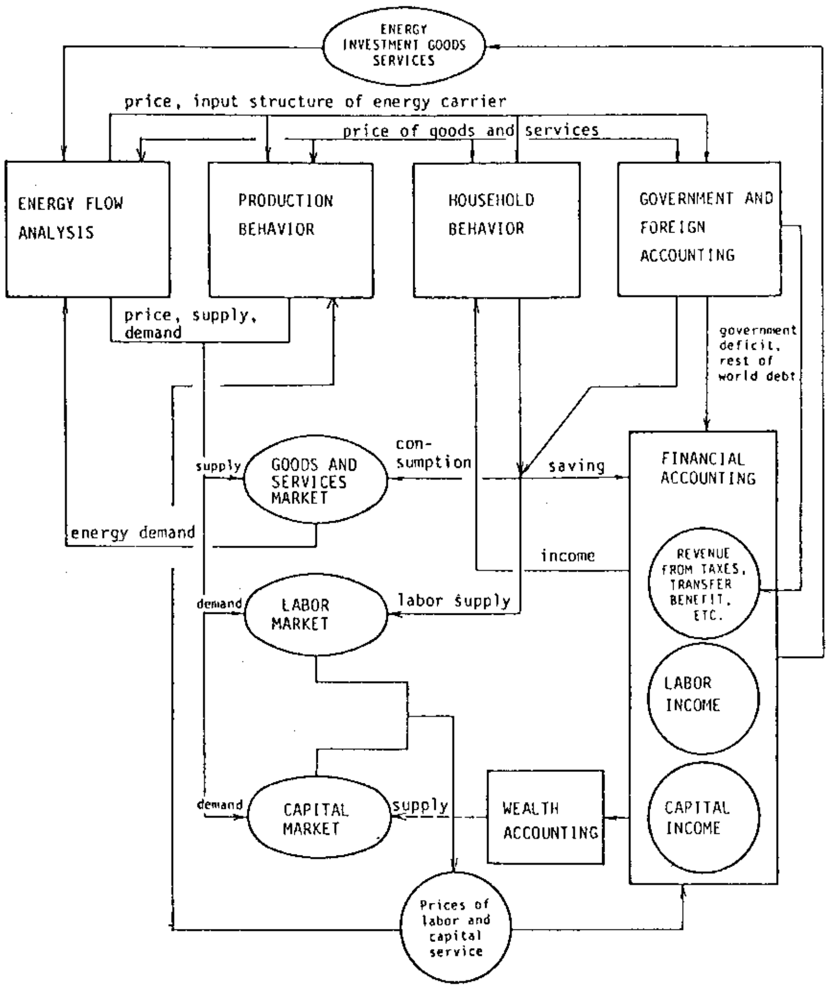


Fig. 3-c) Block Base Representation of Energy-Economy Interaction Model

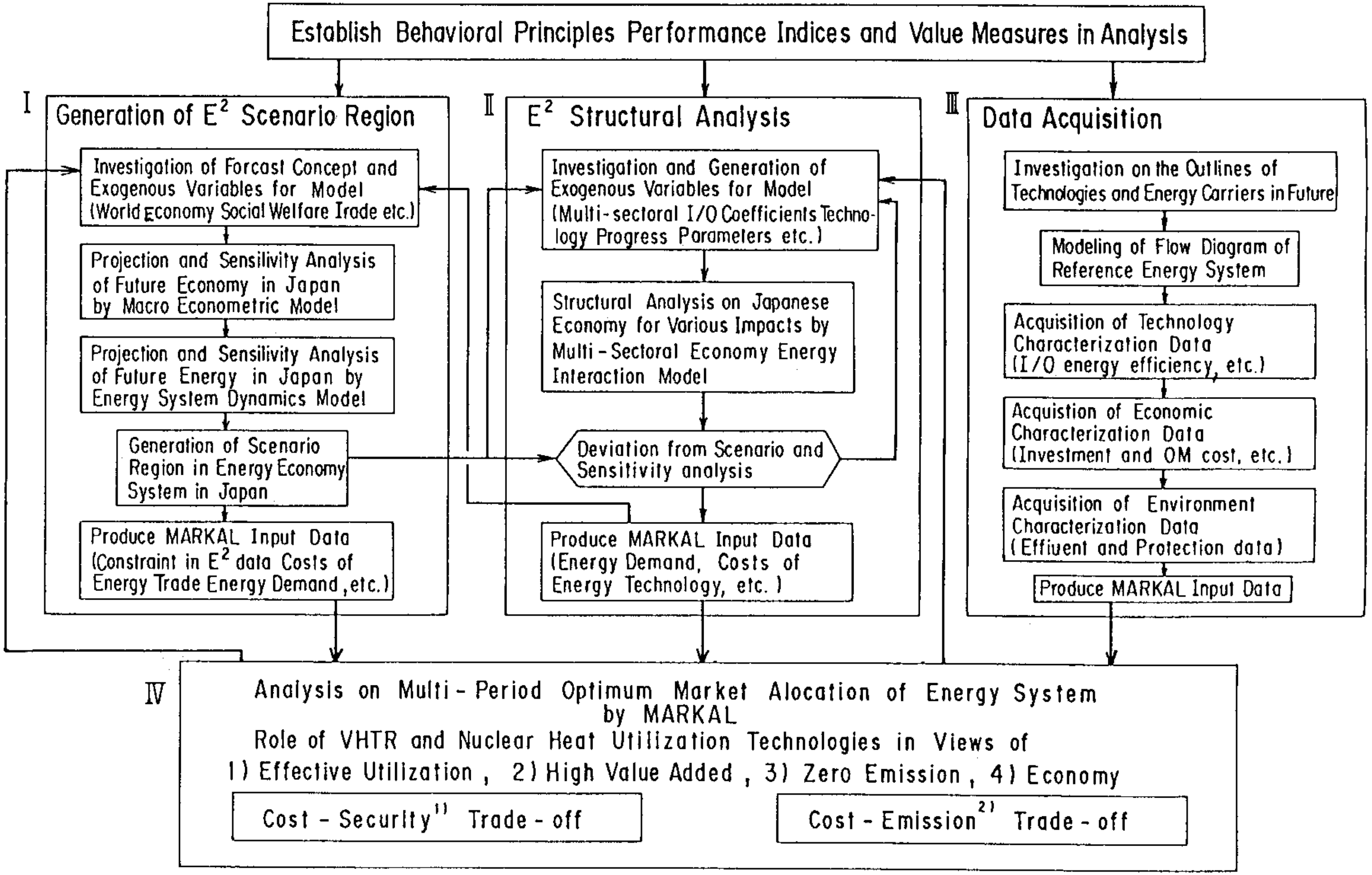


Fig. 4 Breakdown of Study Procedures

1) Total Amount of Import of Crued OIL, LNG and OIL Product

2) Total Amount of SOx, NOx, and CO_2 Emission from Energy System

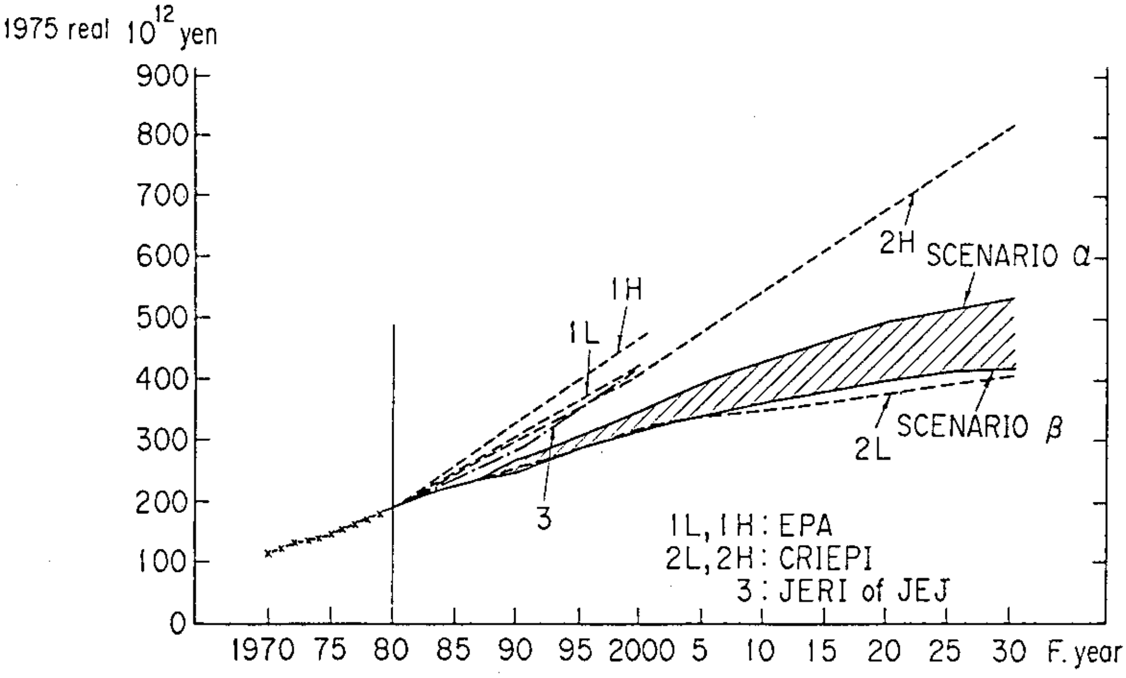


Fig. 5-a) GNE (Gross National Expenditure) Scenarios through the Year 2020

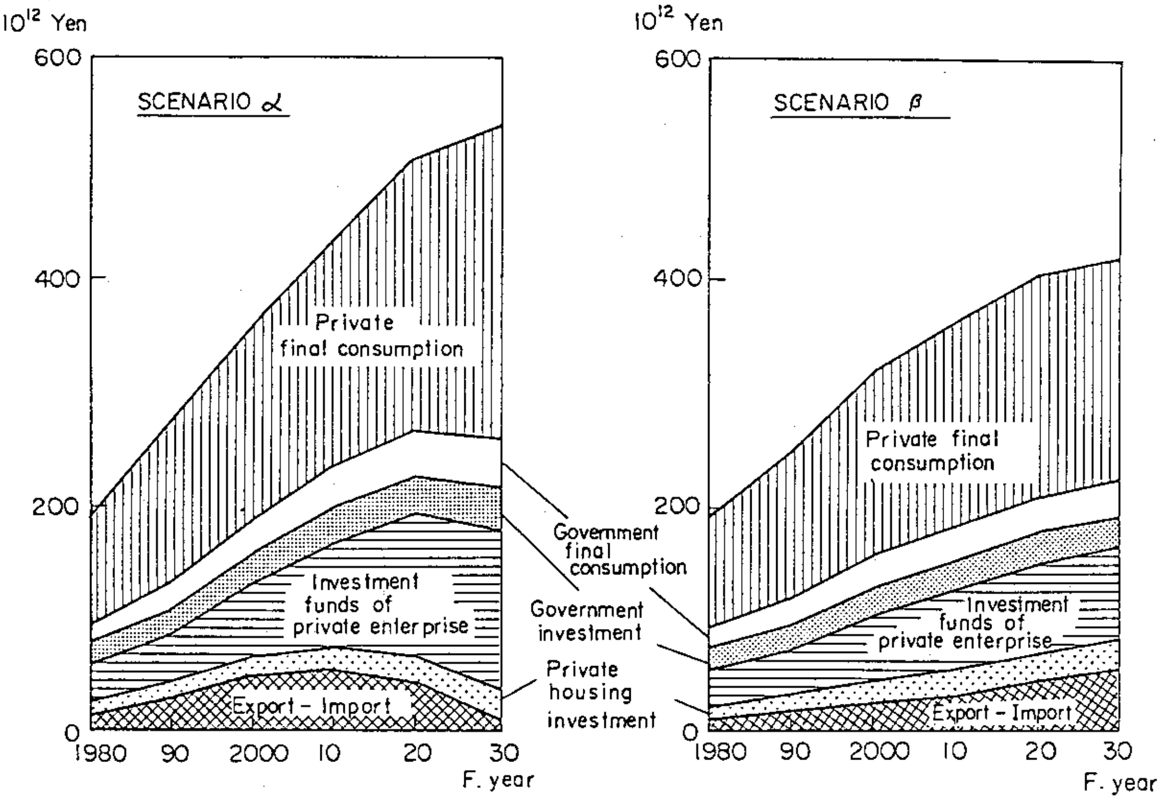


Fig. 5-b) Composition of Gross National Expenditure in Economic Scenario

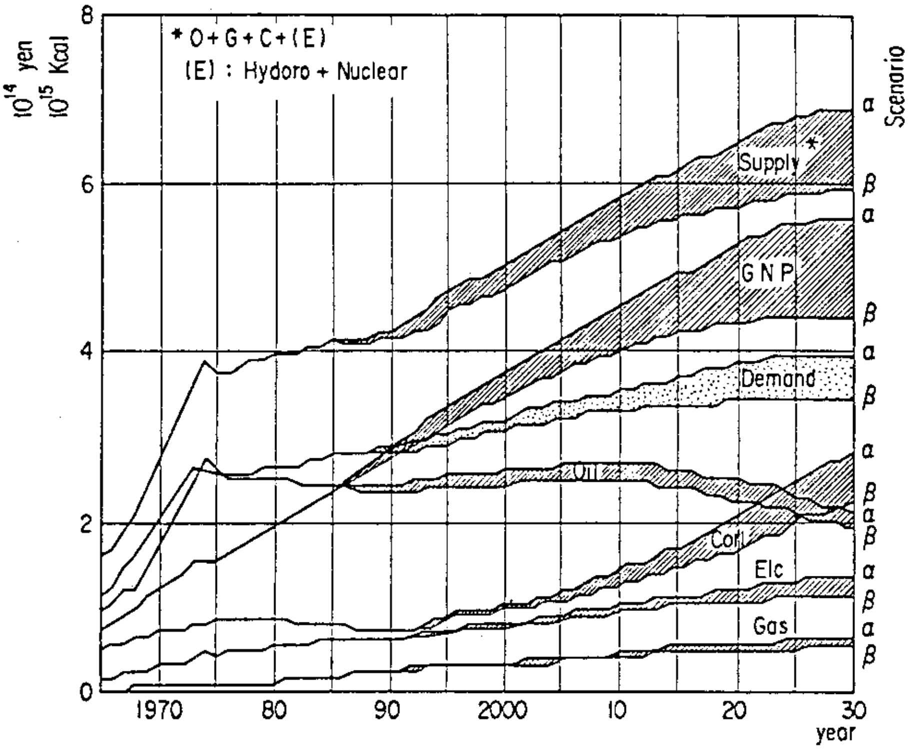


Fig. 6-a) Energy Scenarios on Primary Energy Demand/Supply through the Year 2020

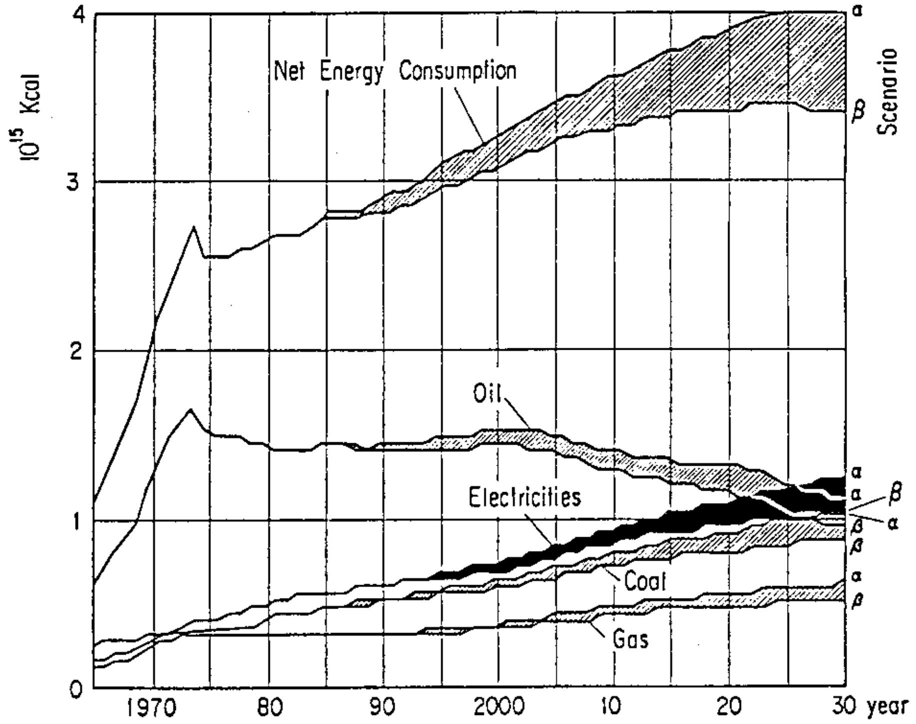


Fig. 6-b) Energy Scenarios on Final Energy Consumption through the Year 2020

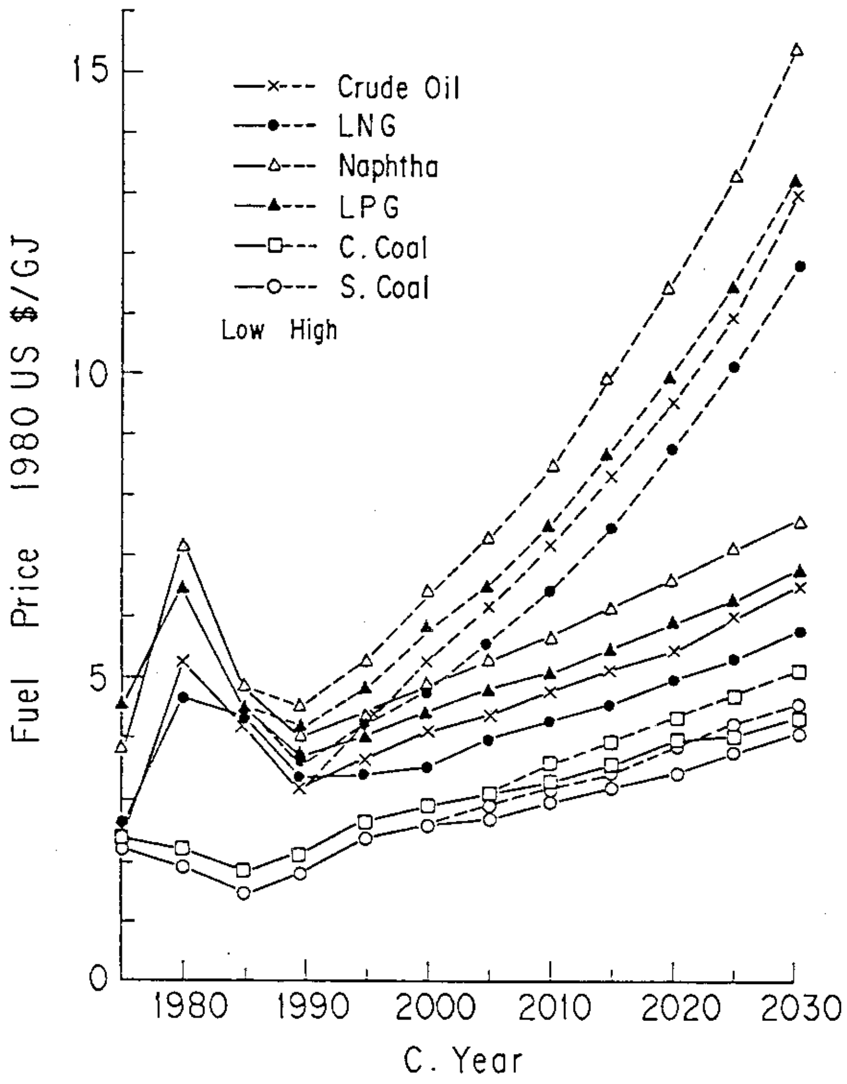


Fig. 7 Price Scenario of Import Energies

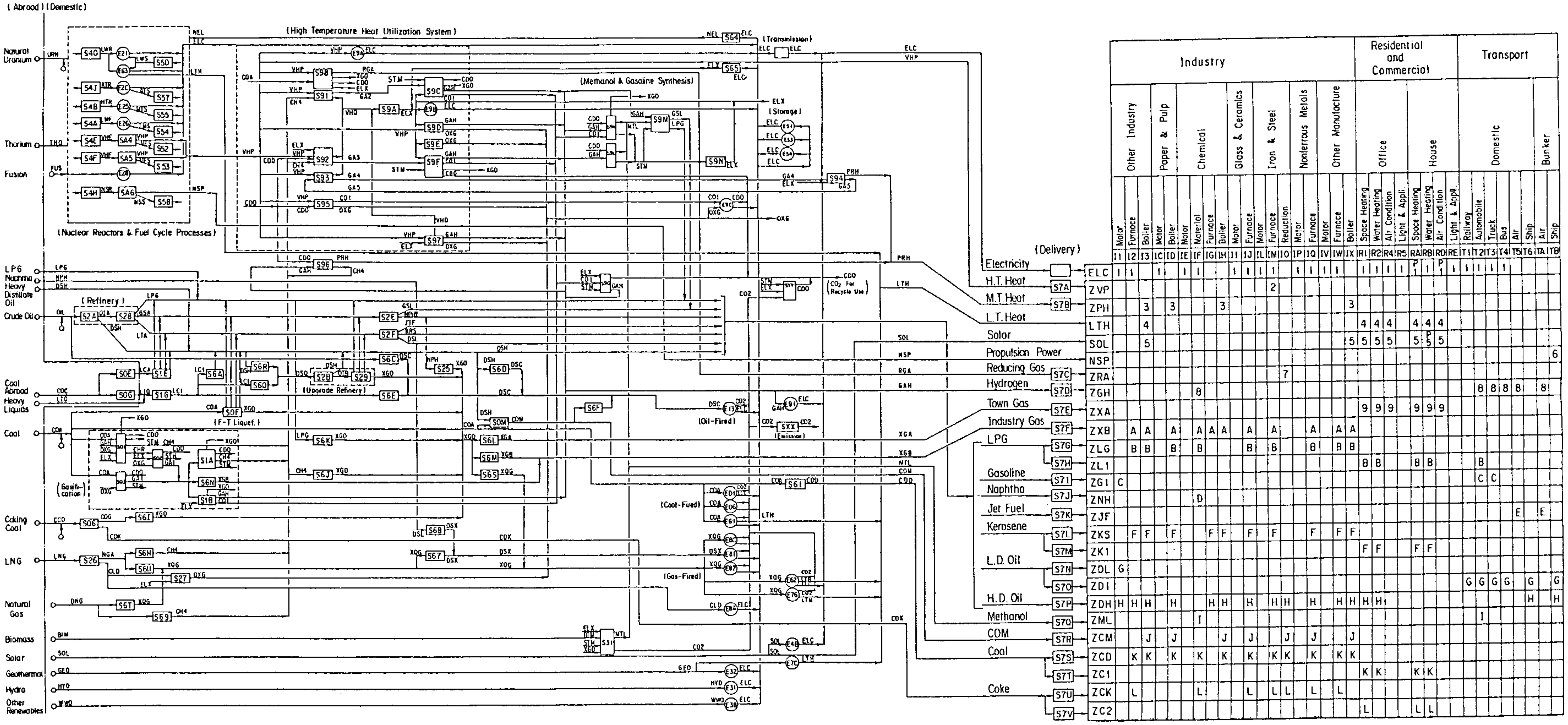


Fig. 8 Detail Flow Diagram of the Reference Energy system

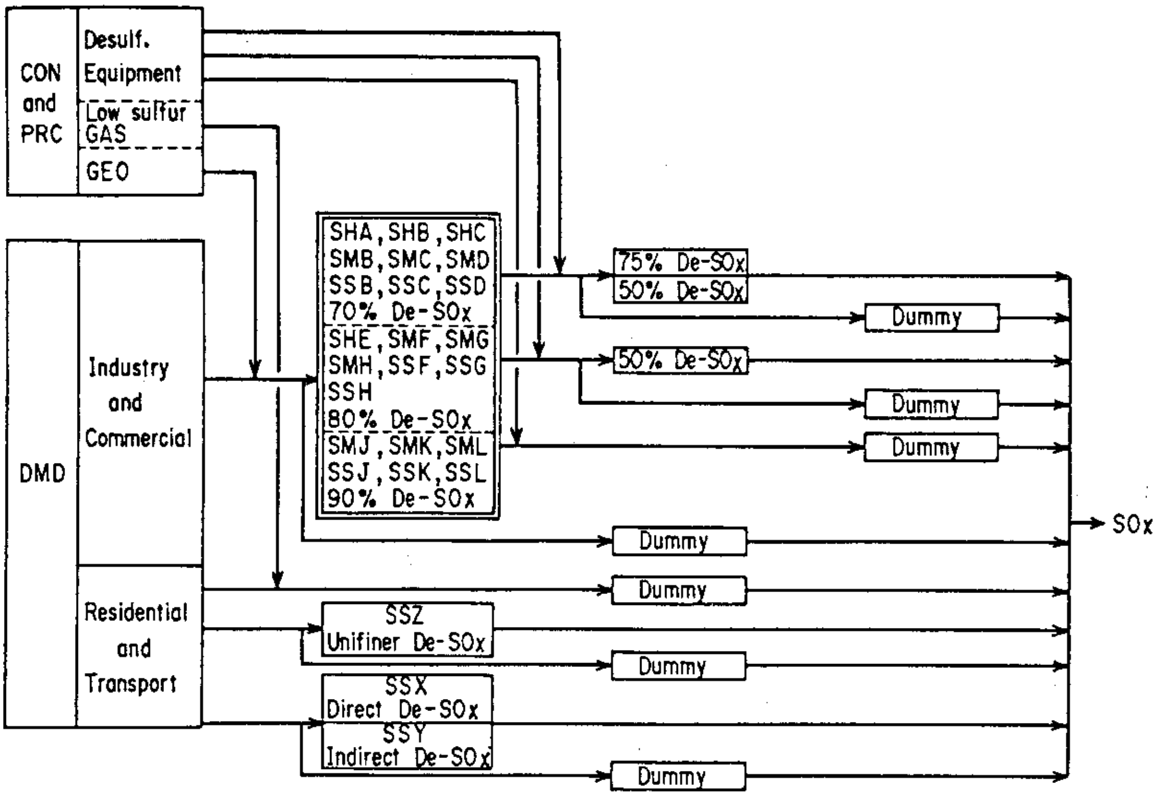
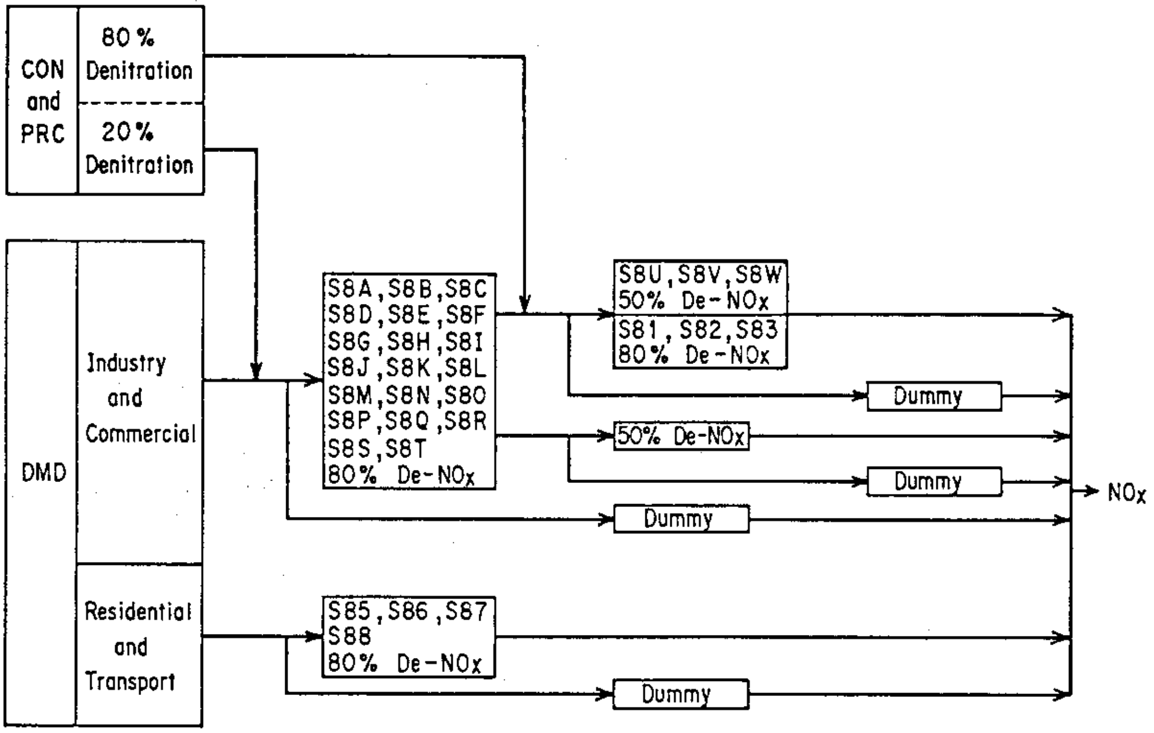


Fig. 9-a) An Outline Flow Diagram of SOx Emission Control Technologies



CON ; Conversion Technologies
PRC ; Process Technologies
DMD ; Demand Device Technologies
Dummy ; Hypothetical By-pass Technologies

Fig. 9-b) An Outline Flow Diagram of NOx Emission Control Technologies

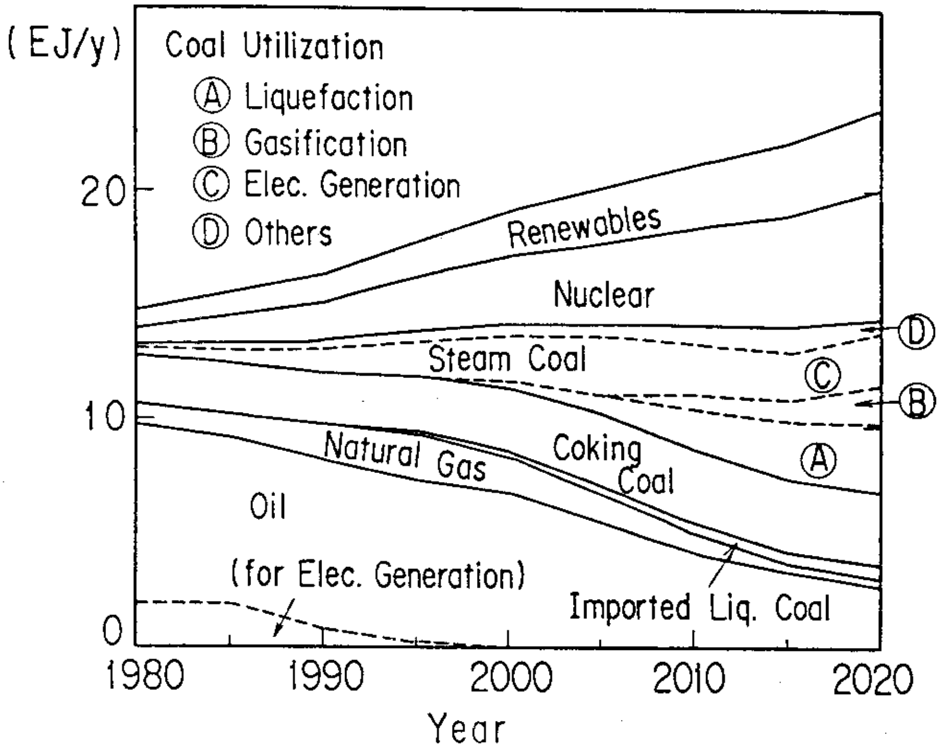


Fig. 10-a) Primary Energy Supply

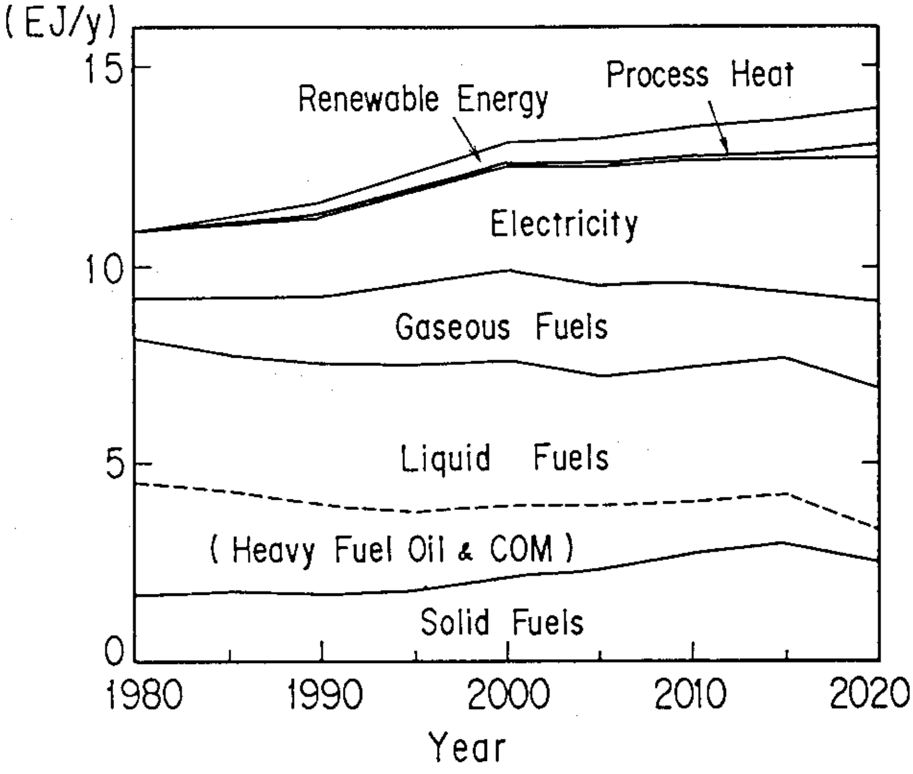


Fig. 10-b) Final Energy Consumption

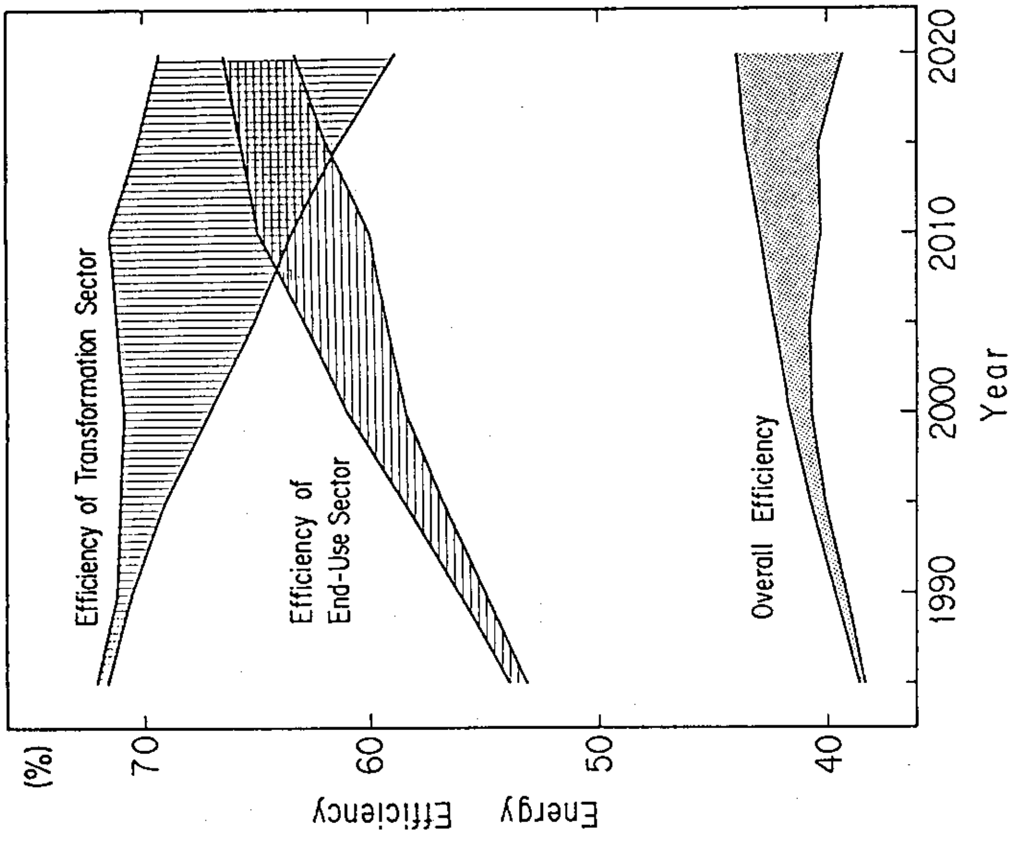


Fig. 11-a) Energy Efficiencies in Optimum Energy Systems

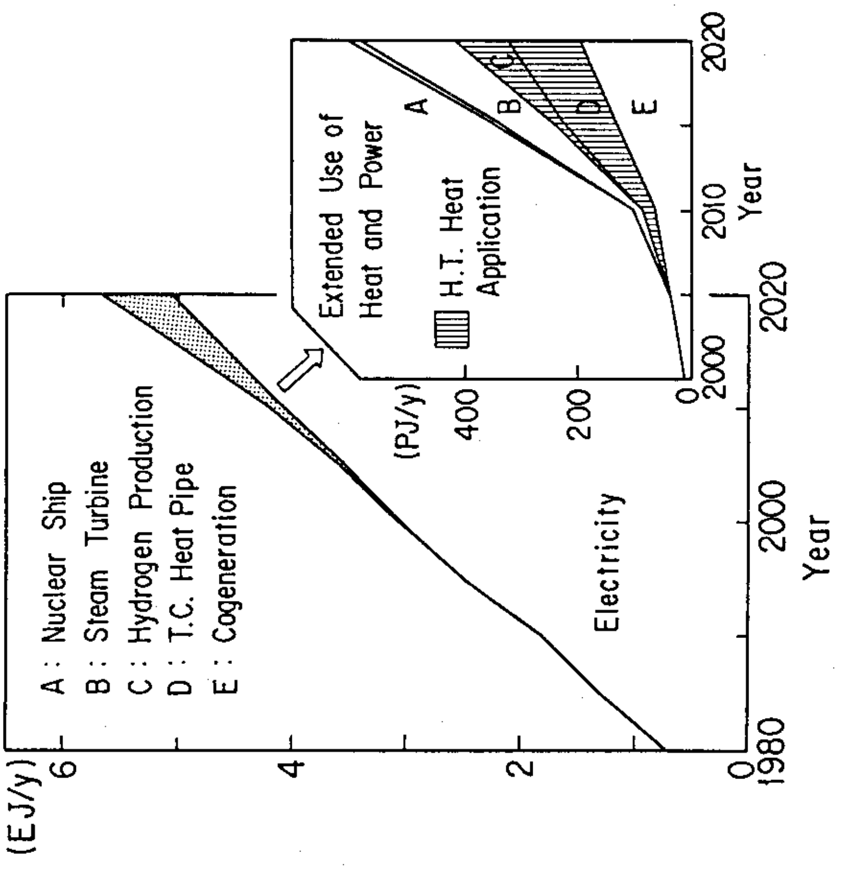


Fig. 11-b) An Example of Nuclear Energy Utilization

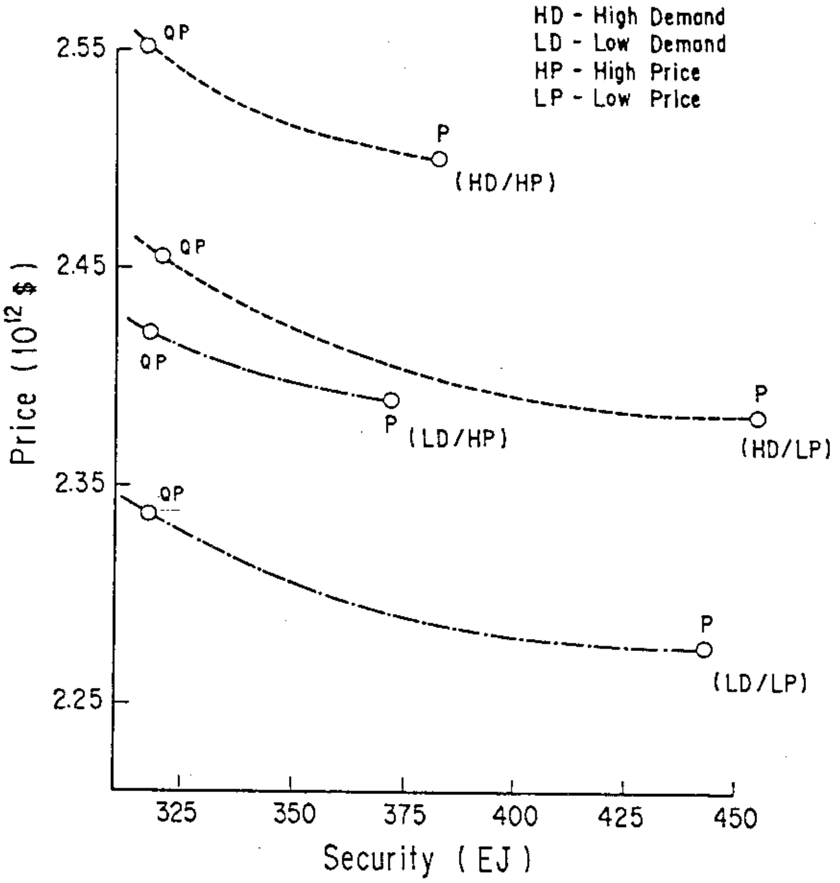


Fig. 12-a) Estimated Cost/Security Trade-off Relationships

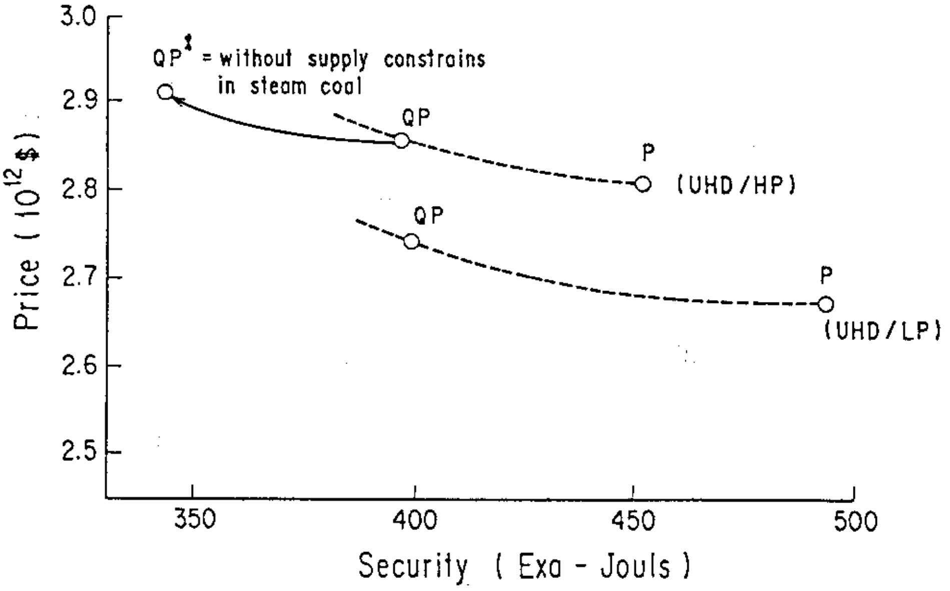


Fig. 12-b) Cost/Security Trade-off with and without a Constrain on the Amount of Imported Steam-Coal

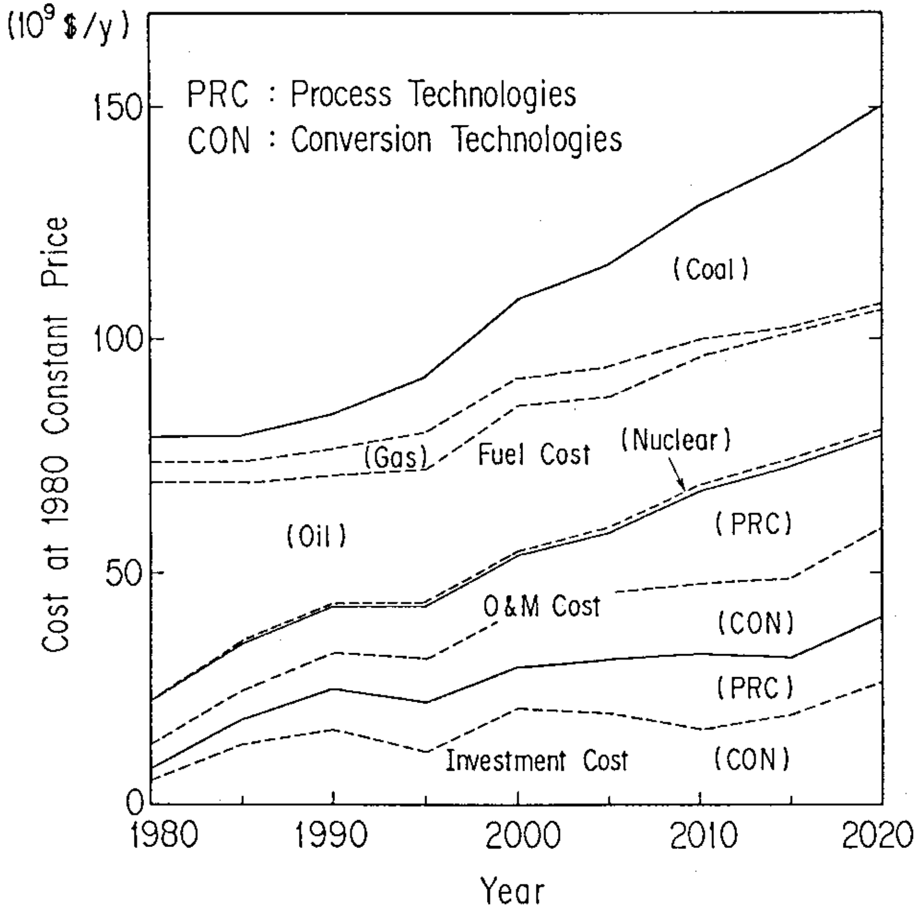


Fig. 13-a) Cost of Energy Transformation System

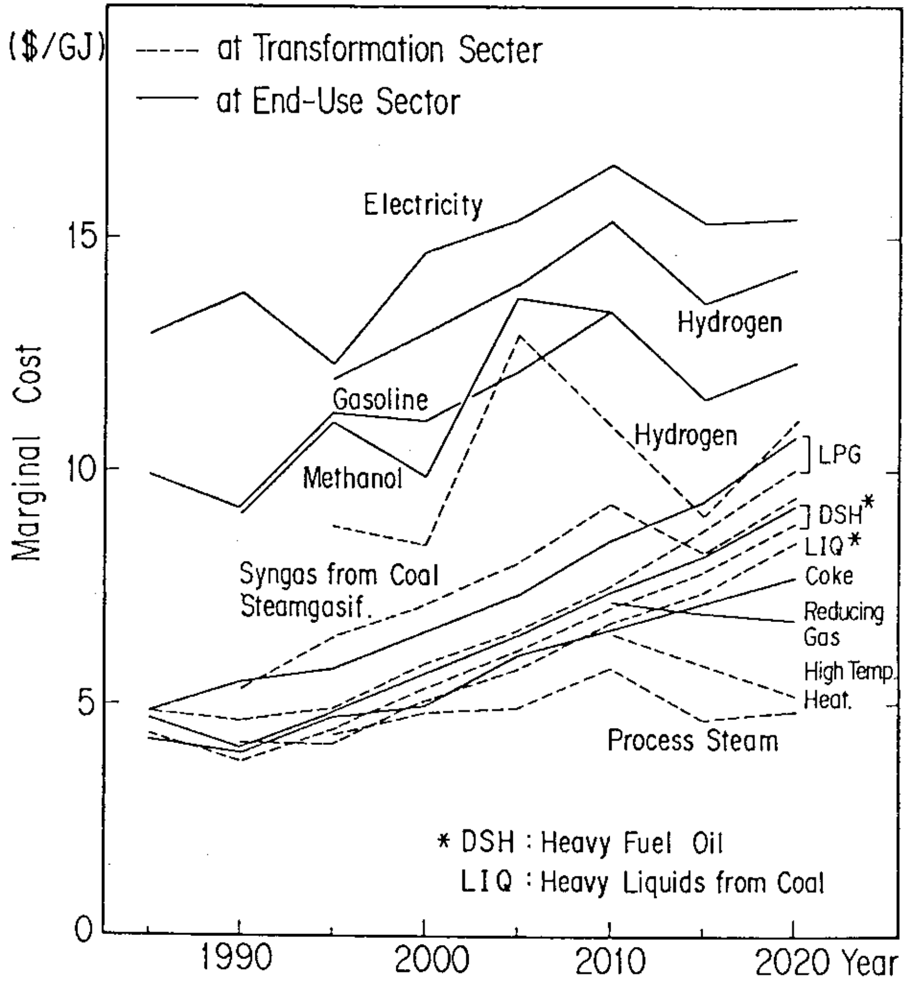


Fig. 13-b) Marginal Cost of Energy Carriers at 1980 Constant Price

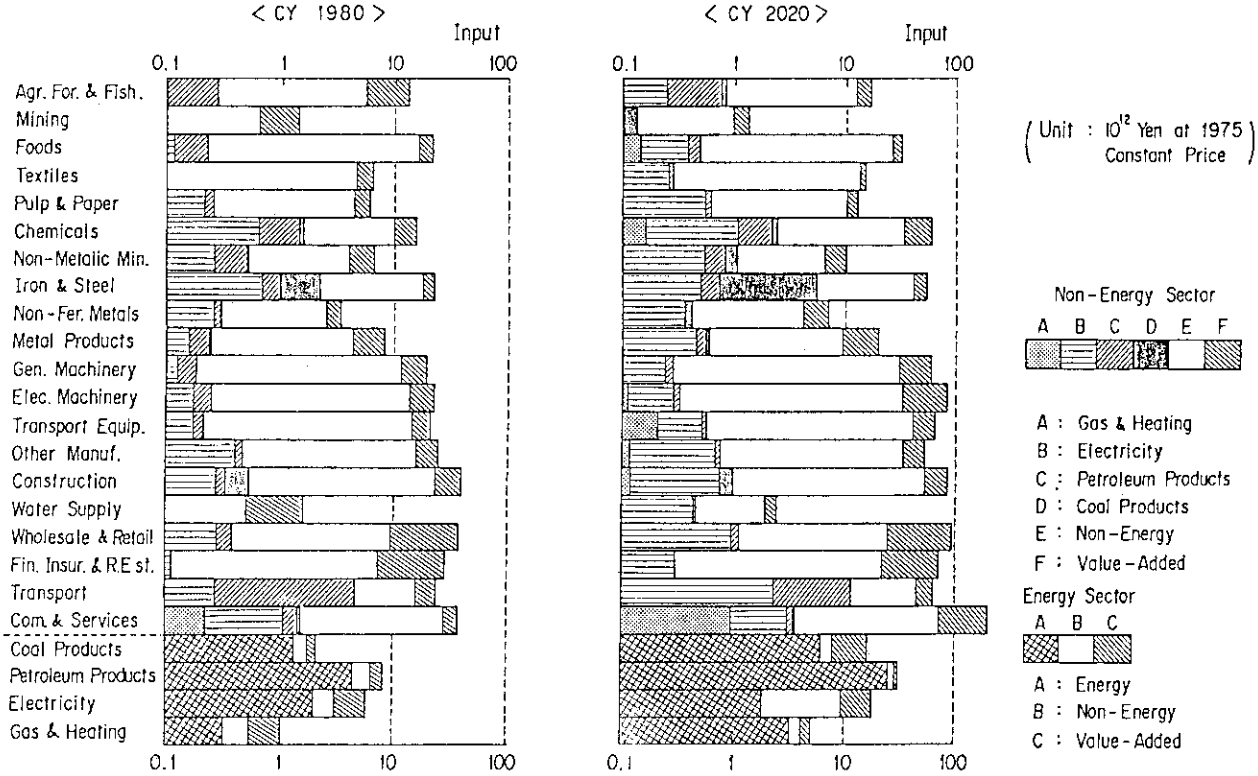


Fig. 14 Input Structures of Industry in CY 1980 and CY 2020

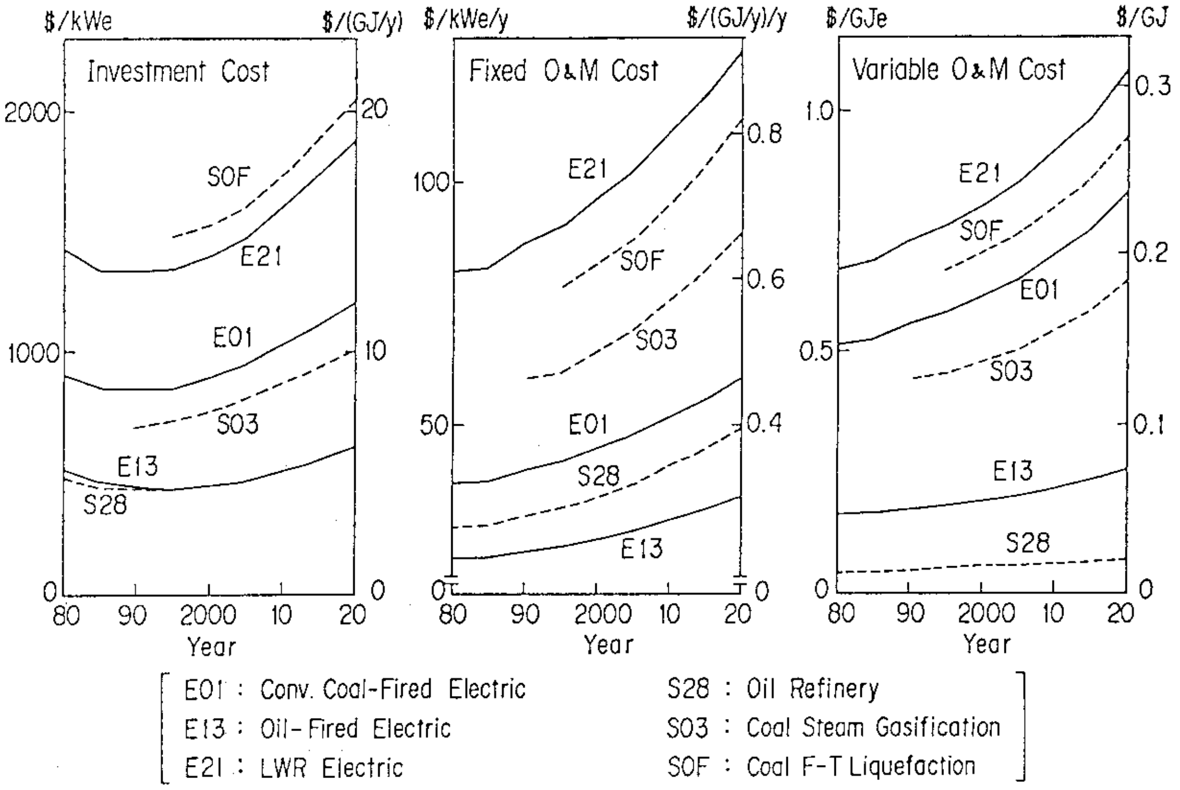


Fig. 15 Evolution of Technology Costs at Current Prices under Long-Term Structural Change in Economy

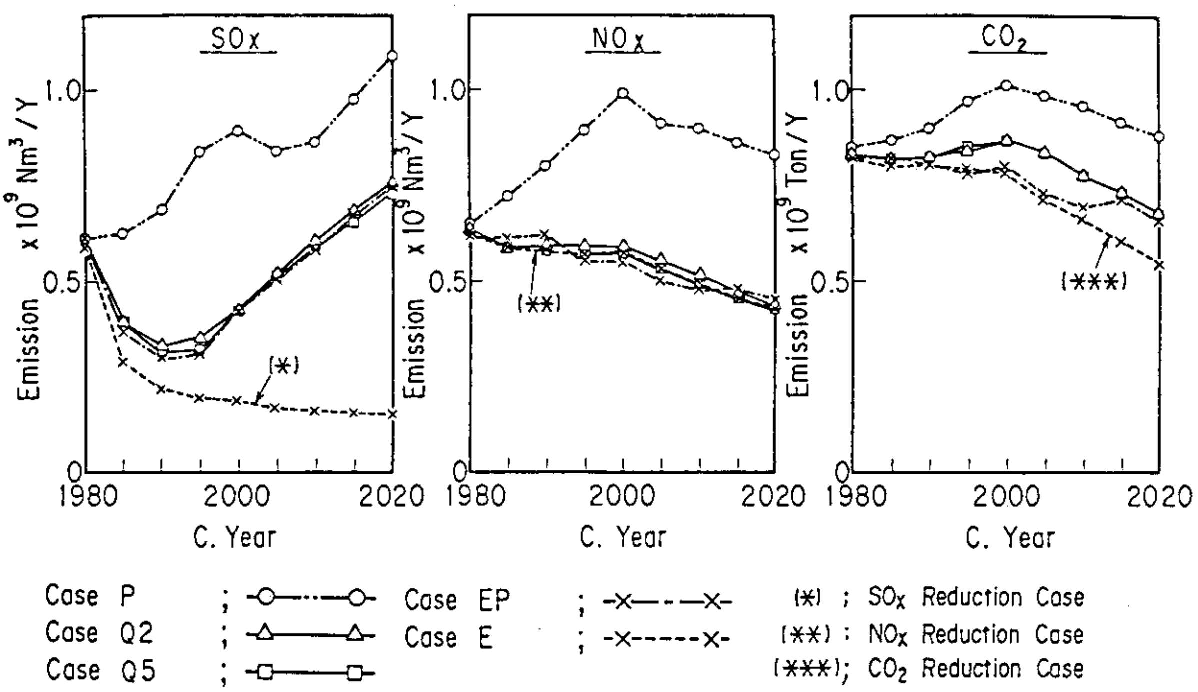


Fig. 16-a) Yearly Change in Amounts of Emission in the case of without Emission Control Technologies (Case 1B)

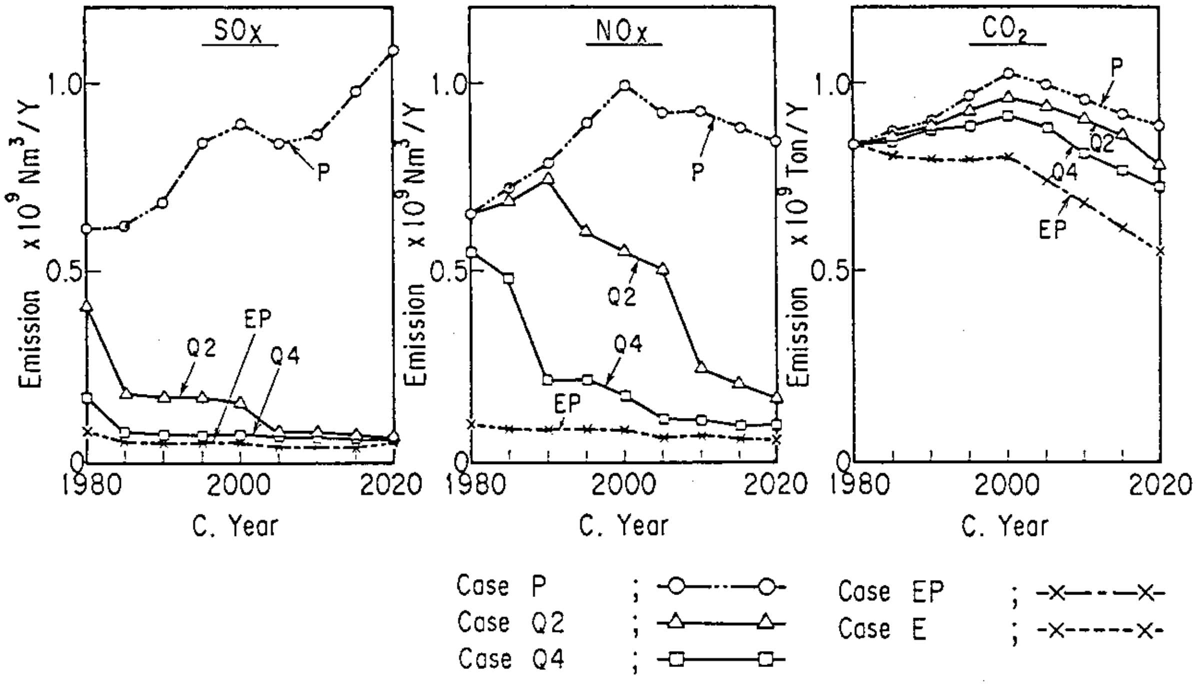


Fig. 16-b) Yearly Change in Amounts of Emission in the case of with Emission Control Technologies

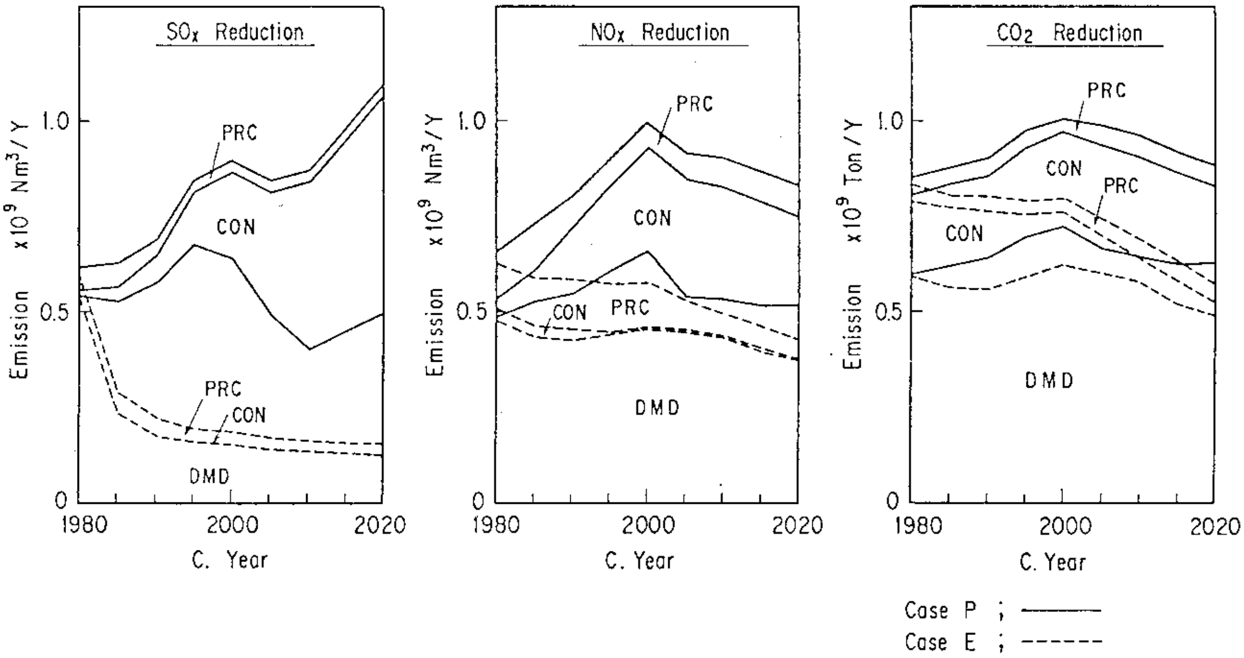


Fig. 17 Yearly Change in the Total Amounts of Emissions by each sector

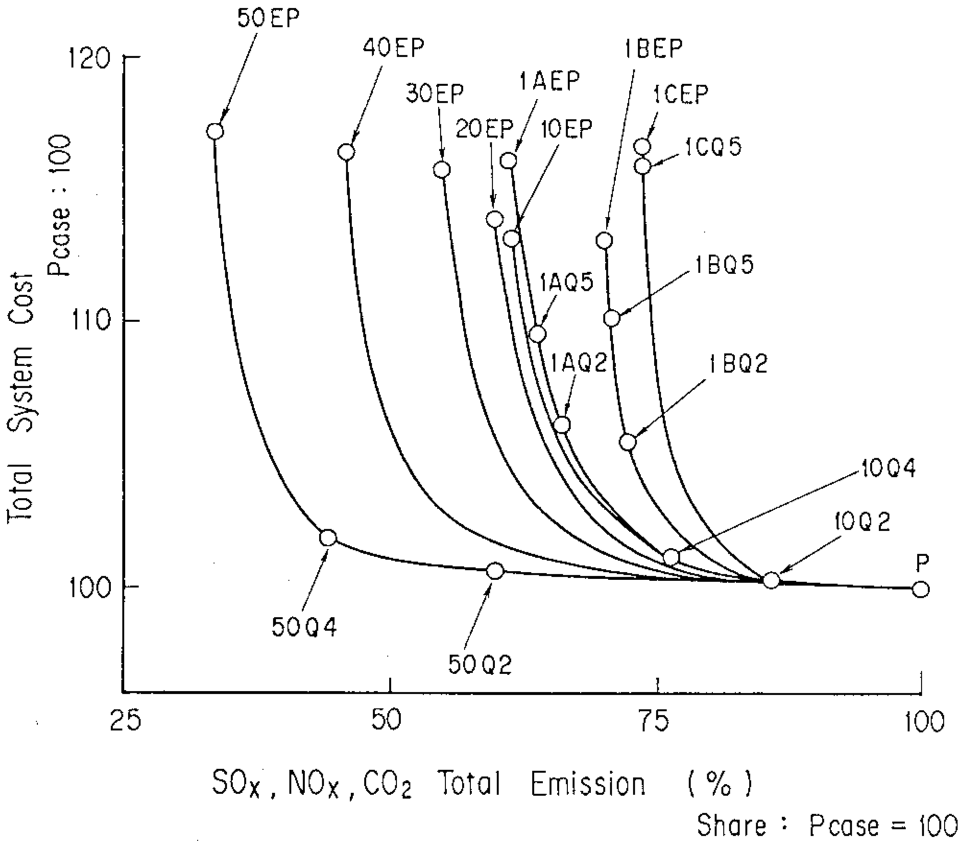


Fig. 18 Estimated Trade-off Curves between Total System Cost and Total Amount of Emissions

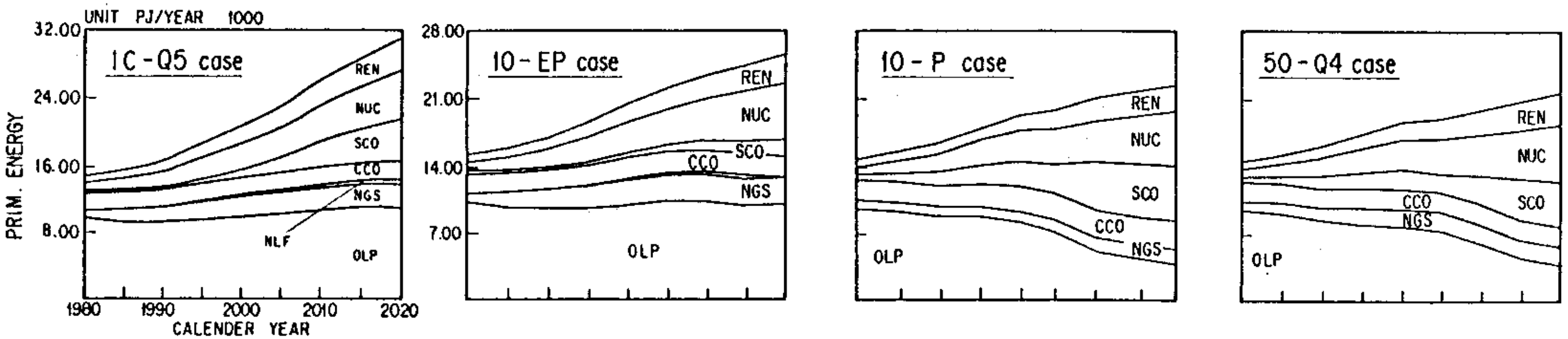


Fig. 19-a) Situation of Primary Energy Supply

OLP = CRUDE OIL AND OIL PRODUCTS
NGS = NATURAL GAS
NLF = NEW LIQUID FUEL
CCO = COKING COAL

SCO = STEAM COAL
NUC = NUCLEAR
REN = RENEWABLE ENERGY

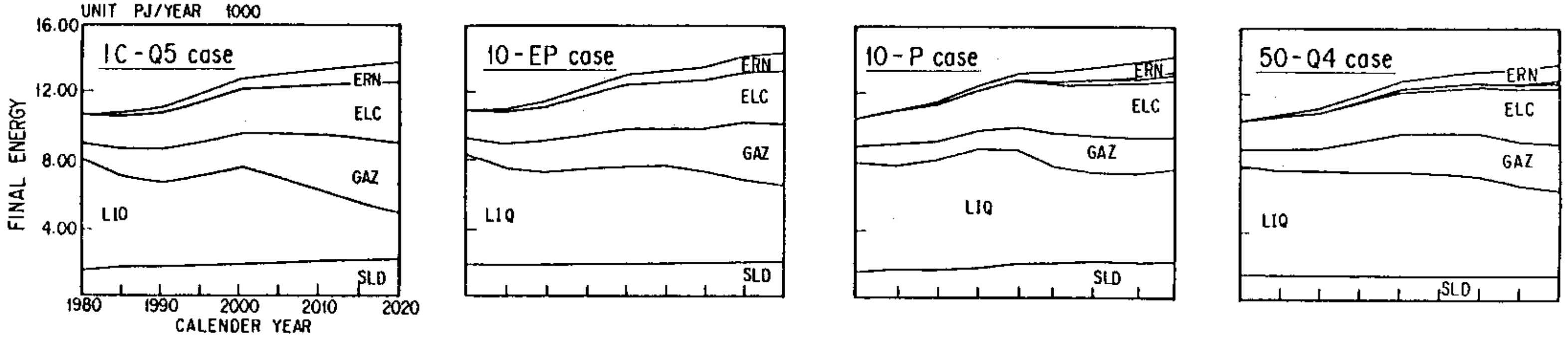


Fig. 19-b) Transition of Final Energy Demand

SLD = SOLID FUELS
LIQ = LIQUID FUELS
GAZ = GASEOUS FUELS
ELC = ELECTRICITY

LTH = LOW TEMPERATURE HEAT
HTH = HIGH TEMPERATURE HEAT
ERN = DECENTRALIZED SUPPLY

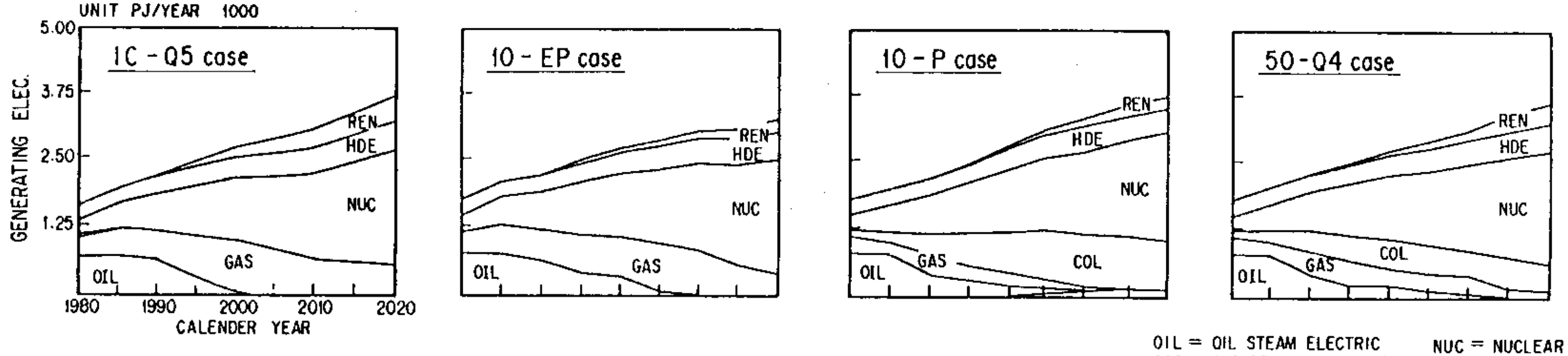


Fig. 19-c) Changes of Composition in Electricity Generation

OIL = OIL STEAM ELECTRIC
GAS = GAS STEAM ELECTRIC
COL = COAL STEAM ELECTRIC

NUC = NUCLEAR ELECTRIC
HDE = HYDRO ELECTRIC
REN = OTHER RENEWABLE ELECTRIC

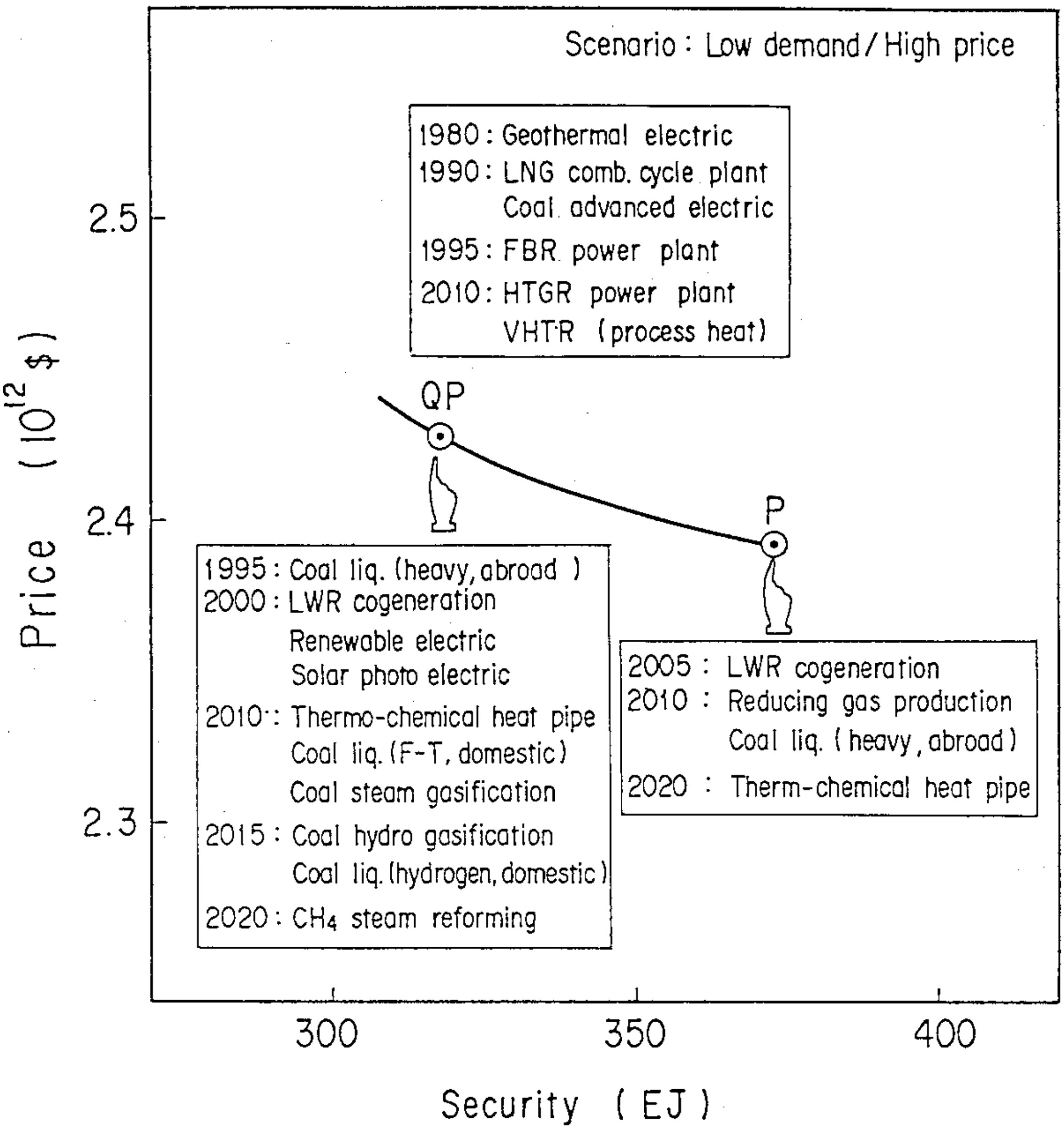


Fig. 20 New Technologies Entering in Price-Security Trade-off

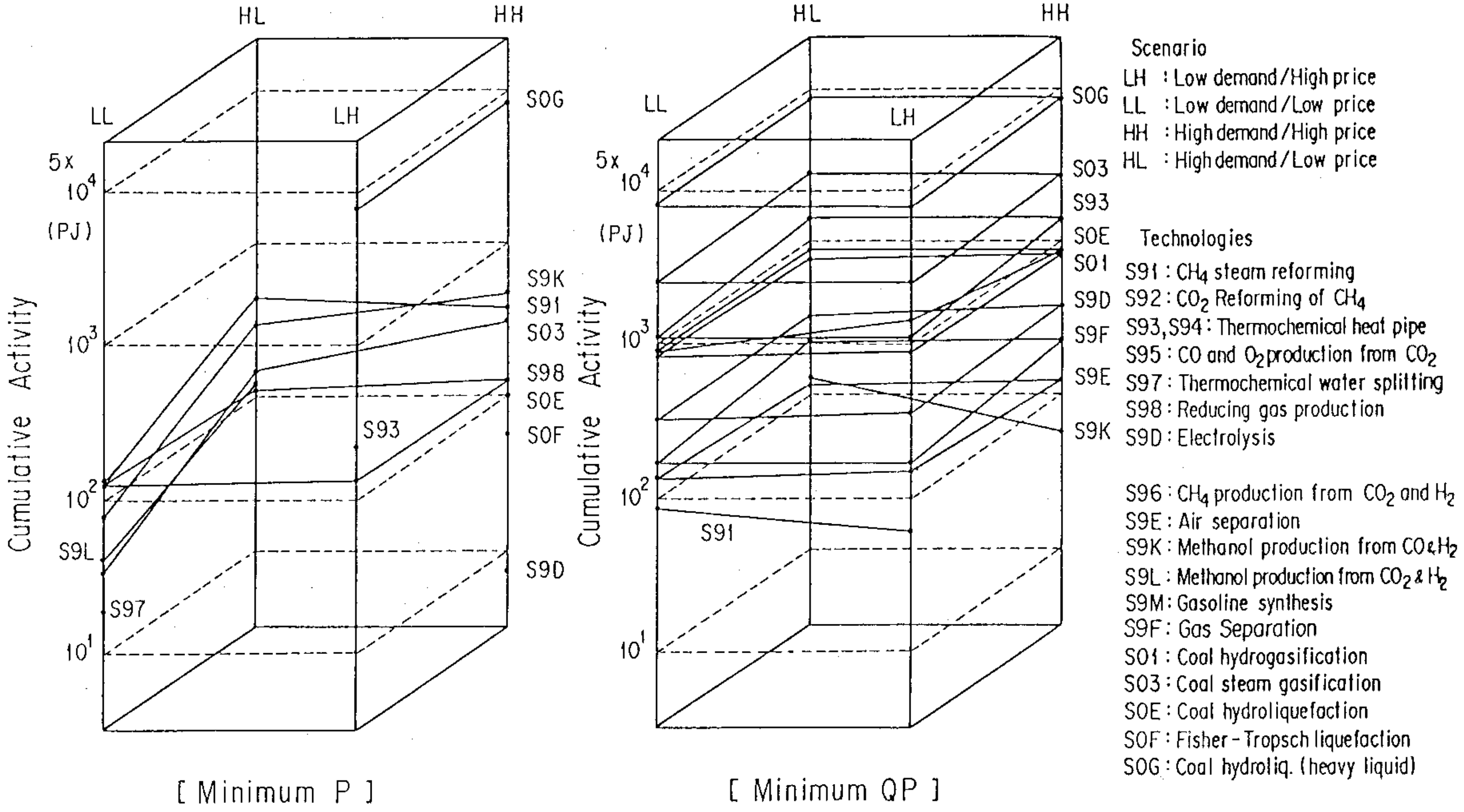


Fig. 21 Implementation of New Technologies for High Temperature Nuclear Heat Utilization and for Coal Conversion

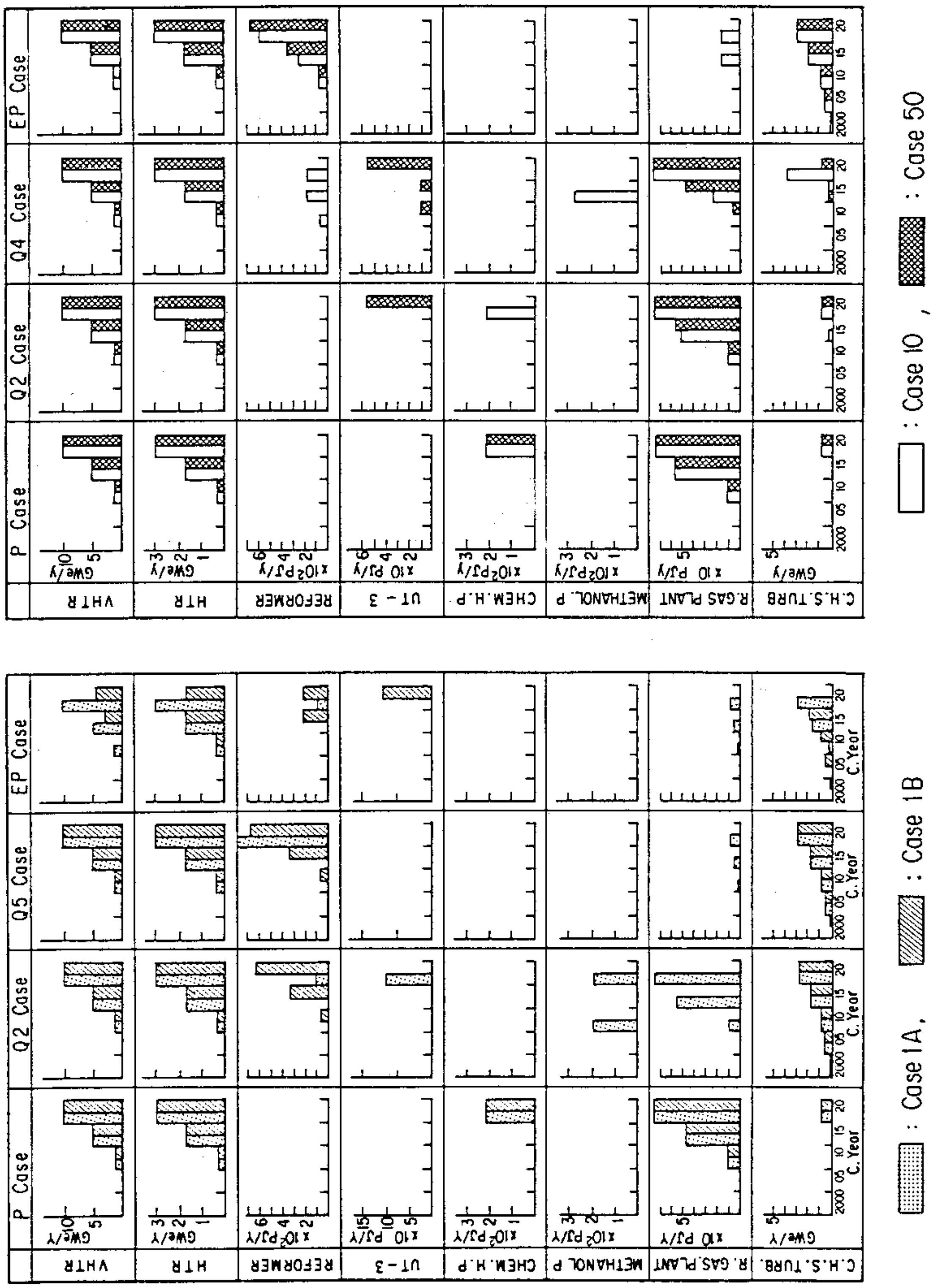


Fig. 22 Installed Capacities of IES Technologies at the Case of Environmental Emission Control