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OECD/IEA/ETSAP ENERGY-ENVIRONMENT SYSTEMS ANALYSIS

— TOWARDS FOSSIL-NUCLEAR SYMBIOSIS —

December 1988

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OECD/IEA/ETSAP Energy-Environment Systems Analysis
-Towards Fossil-Nuclear Symbiosis-

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Fuel supply and demand mix as well as energy technology configuration are analyzed by the MARKAL model for the future Japanese energy system, when reduction of environmental emissions is taken into consideration. The Reference Energy System (RES) covers whole sectors, i.e., fuel conversion and energy transformation, industry, residential and commercial, and transportation sectors. Environmental emissions considered here are SOx, NOx, CO_2, and radio activity, and the time horizon is an interval from 1985 to 2030.

Both SOx and NOx emission can be reduced much by present art of reduction measures. From the view points of cost effectiveness, abatement technologies including fluegas treatments take the highest priority and fuel switching and technology substitution follow in this order. For CO_2 reduction, both nuclear and renewable energy technologies are essential among them.

Keywords : Energy-Environment Systems Analysis, SOx, NOx, CO_2 Emission, Optimization Analysis by MARKAL

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OECD/IEA/ETSAPエネルギー・環境システム解析
―化石燃料と原子力の共生にむけて―

日本原子力研究所動力炉開発・安全性研究管理部
安川　茂・佐藤　治・田所　啓弘
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（1988年12月8日受理）

環境排出物の削減を考慮した場合の燃料の需給構成ならびにエネルギー技術の構成を日本の将来のエネルギーシステムを対象にMARKALモデルで解析した。基準エネルギーシステム（RES）は，燃料の転換，エネルギー変換，産業，民生，輸送の全部門を含んでいる。取り上げられた環境排出物はSO_x，NO_x、CO_2，および放射能であり，解析対象の期間は1985年から2030年までである。

SO_xとNO_xの排出は現状の排出抑制技術で充分に削減できる。費用対効果の観点からは，排ガス処理を含む排出抑制技術が最高の効果を持ち，燃料転換，技術代替がこれに続く。CO_2の削減に対しては原子力と自然エネルギー技術が不可欠である。

本報告書は1988年10月31日，日本原子力研究所東京本部で開催されたIEA/ETSAP（国際エネルギー機関／エネルギー技術システム分析プロジェクト）会議において発表，配布された。

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1. Introduction

As seen in the warning of "Energy in a Finite World" [1], our energy system is thought still to depend on fossil fuels heavily for next half century. However, a part of the earth is going to deteriorate by environmental pollutions such as acid rain, and many people worry this. Excessive utilization of fossil fuels, along with other environmental disruption such as tropical deforestation and various trace gas emissions, would lead to the acceleration of the global environmental problems further, i.e. the surface temperature rise, acid rain precipitation, ozone depletion in the stratosphere, soil destruction, etc..

Since the industrial revolution, people have improved their social welfare through widening energy use and rising production activity with application of science and technology. Especially, the fluid fuel revolution by oil and gas brought us unmeasurable conveniences. Further, the experiences of releasing nuclear energy as well as of harnessing solar energy make people conceive energy resourse to be inexhaustible.

In reality, however, instead of such aspiration pepole have confronted with large scale accidents such as at Chernobyl, and they are compelled to think over the consequences associated with them. In this circumstance, if people wish to continue further development of economy and society, they must pay more keen attention than as ever on the course of energy utilization, which has been apt to pursue low price, aboundancy, and conveniency instead of seeking cleanliness and safety.

The concept what is called the best mix will serve as most fundamental tool for realization of the above course, and the most essential point in it is to show the way how to compromize the advantage and the disadvantage of each energy resource complementarily. As an example, we can consider the Integrated Energy System (IES) which aims at fossil fuel nuclear energy symbiosis, i.e. the high temperature nuclear heat in the IES is used to reform fossil fuel and to produce hydrogen, and the reformed gas and hydrogen are utilized for synthesizing methane and methanol which are clean energy carriers with high heat content and low CO_2 emission. Thus, we can maintain the conveniency in energy use through continueing fluid fuel utilization on one hand and rely on the abundancy given by nuclear energy on the other hand simultaneously. Extending this concept one step ahead, we may even convert CO_2 gas into fuel materials.

Our energy system must overcome various constraints if we desire the best mix of energy utilization. For the investigation of the impact brought by such constraints, we have made several kinds of analysis. However, most of them were the analyses from viewpoints of technology and economy [2]. This time, on the contrary, we place our studying objective in investigating optimal course of fuel mix and energy technology selection in our future energy system when we are taking into account environmental constraints. The focussing point in the study will be a tradeoff relationship between emission reduction and system cost, and, if possible, we will resolve the relationship into individual contribution, corresponding to emission reduction method such as fuel cleaning, fuel switching,flue gas treatment technology, energy technology substitution, recycling use of emission, energy conservation, etc..

Just now, we emphasized the importance of seeking the best mix of energy utilization. However, if we wish to seek it under the condition of taking into account the global environmental impact, we may need a global analysis covering years more than a half century from now, and also in its analysis must we include not only direct and/or indirect activities related to energy production and utilization but also non energy acivities, for an instance, our daily activity of using hair spray. It may need interdeciplinery knowledge for us, if we wish to conduct such analysis. Our standpoint to conduct a present energy environment analysis, however, is not to visualize an ultimate fuel mix based on global environmental analysis but to show a possible pattern of fuel utilization and energy technology configuration in a time period, i.e. over 20 to 30 years from now, through dynamics analysis of SOx, NOx, CO_2 emissions. On that occation, we will treat such global environment impact as an external constraint, for an instance, an upper bound for SOx, NOx, CO_2 emission in the MARKAL run.

Based on the above assumption and the recognition, we carry out our study. In the following, analytical method, scenario analysis, evaluation of results will be explained.

2. Analytical Method

2.1 Reference Energy System

It is inevitable for us to introduce more or less a model for our national energy system because it encompasses a variety of configuration. We call such a model as a Reference Energy System (RES).

In preparing a RES, we are taking into account the following considerations: (i) The categorization of enduse sector is made reflecting functional use of energy. (ii) Primary and secondary energy are categorized by their carriers such as coal, oil, gas products as well as electricity and heat, and if necessary they are divided more, for instances, into low temperature heat, intermediate temperature heat, high temperature heat, etc.. (iii) In order to make fuel selection flexibly, plural demand divices are prepared for each single demand category at the enduse sector. (iv) For transportation and distribution as well as for storage of energy carrier, different scale of capacity is possible.

As the fifth item, energy conversion sector is divided into two major parts, i.e. electricity and heat generation as the first and fuel refinery and processing as the second. The former on global environmental analysis but to show a possible pattern of fuel utilization and energy technology configuration in a time period, i.e. over 20 to 30 years from now, through dynamics analysis of SOx, NOx, CO_2 emissions. On that occation, we will treat such global environment impact as an external constraint, for an instance, an upper bound for SOx, NOx, CO_2 emission in the MARKAL run.

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As the fifth item, energy conversion sector is divided into two major parts, i.e. electricity and heat generation as the first and fuel refinery and processing as the second. The former is further divided into several parts according to the difference of input fuel, i.e. fossil fuels, nuclear and renewable energy, and it can also be categorized as the sectors of electricity or heat generation or a coupled production of heat and electricity and a centralized site or a decentralized site as well. The fuel refinery and processing part consists of those processes as oil refinery, upgrading process of oil products, coal liquefaction and gasification, coaking coal production, consummer gas production, nuclear fuel cycle processes which are further divided into an up-stream part and a down-stream part, gasoline synthesis process, etc.. In Fig. 1, we show the RES flow diagram.

For the study of the meaning on complementary use of fossil fuel and nuclear energy, we have introduced an IES. The IES includes the following energy technologies: high temperature gas-cooled reactor supplying high temperature nuclear heat; hydrogen production processes such as steam-methane reforming, water thermal splitting process UT-3, high temperature electrolysis; reducing gas process for iron reduction; He gas and steam turbine combined cycle power plant. Also, it includes methane and methanol synthesis process of which input gases are syngas and carbon dioxide as well. Chemical heatpipe can also be used for transportation of intermediate heat to enduse sector. In the IES, H_2 gas can be utilized not only for fossil fuel reforming but also for converting CO_2 to such fuels as methane and methanol, and both CO and O_2 gas can be utilized as input fuel for a high efficiency CO gas turbine combined cycle power plant.

As for the enduse sector, we first divide it into the following four subsectors, i.e. industrial, commercial, residential and transportation sector according to the institutional classification, and then categorize each of the sectors by technology classification as follows: In the industrial sector, the subdivision is made for motor, boiler, furnace as general part, for melting and reducing devices in iron and steel making process, for chemical feedstock, for nonferrous metal electrolysis, and for cement kiln. Also, such by-product gases as BFG and LDG are recyclingly used at auto-generating power plants and/or as industrial gases. In the residential and commercial sector, such subdivisions as lighting and motor power, space heating, water heating, and airconditioning are made by the category of energy use. In the transportation sector, the subdivisions of domestic part and the rest are made first. Further, the domestic part is subdivided into the enduse devices of rail way, automobile, bus and truck, airplane, and ship, and the rest into airplane and ship. To each of demand devices, appropriate energy carriers supply necessary amount of energy.

2.2 Energy Technology Characterization

About 280 energy technologies and 16 emission control technologies are included in the RES. If we classify them according to the MARKAL category, they can be divided into 33 conversion technologies (CON), 142 process technologies (PRC), and 120 demand devices (DMD).

Each technology is characterized by technical data of which items are scale of capacity, technical life time, input and output of fuel or electricity and heat generation efficiency, maximum capacity availability factor, economical performance indices such as capital cost, operation and maintenance cost, the latter being further divided into a fixed term and a variable term, fuel related cost, and environmental indices such as emission factor, emission control cost, etc..

In technology characterization, we have taken into account the following considerations: (i) proper selection of representative technology and evaluation of average characteristics and their deviation, (ii) treatment of nonlinear property in characterization, (iii) scale of economy, (iv) heat content standard, (v) evaluation timing and exchange rate, (vi) treatment of auxiliary energy.

As for item (i), we used the experiences compiled till previous studies [3]. However, concerning environmental emission factors and cost data, we have revised again the MARKAL data base, utilizing the information supplied by the Institute of Behavioral Science [4], where emission factors and costs are processed from various statistics and technical data. As for item (ii), we must first admit the fact that our present model can not treat this property endogeneously. However, we can simulate this indirectly through a sensitivity analysis. As for item (iii), we can simulate it approximately through processing economic performance indices as well as setting capacity upper bound. As for item (iv), we follow on net calorific base. As for item (v), all economical data are first estimated by Japanese yen, then, they are converted to US dollar with the 1985 exchange rate. As for item (vi), basically we follow on net efficiency base. But, in the case of emission control technology which is treated separately from the mother technology, the energy input as auxiliary use is given endogeneously, i.e. the level of the energy input depend on its activity. Examples of technology characteristics are shown in Table 1.

2.3 Emission Control Method

As for environmental emission control, we can consider several methods, i.e. (i) fuel cleaning before combustion, (ii) fuel switching to low sulfur fuel (e.g. switching from coal to natural gas), (iii) improvement of fuel combustion (e.g. low NOx burner, AFBC, PFBC, IGCC), (iv) flue gas treatment (e.g. FGD, SCR), (v) technology substitution (e.g. from fossil fuel to nuclear and/or renewable energy technology), (vi) recycling use of flue gas (e.g. CO_2 recycling use), (vii) energy conservation, etc..

In the analysis of emission reduction by the MARKAL model, we divided energy technologies into the following two groups. The first group has emission control technology within it, i.e. the emission control technology is not prepared separately, so that the change of its characteristics due to the inclusion of emission control technology is reflected to those of mother technology. The second group treats emission control technology independently as an annex to mother technology. Fig. 2 shows technology connection representing the above concept.

We discriminate the emissions of residual capacity from those of newly installed capacity and apply emission control technologies only to the latter. The reason is as follows. So called residual capacity is defined as such capacity of energy technology which was installed before the planned time period but is continueing its service operation. In other words, it is the sum of capacities which are subject to the environmental standards at different past years. This implies that some part or even major part of it has already control technologies and the emission factor of it is determined as an average on such capacities. Accordingly it is not appropriate to apply additional control technologies on it in the same way as new capacity. The purpose of the above descrimination is to make the residual capacity adjusting its environmental emission through retrofitting its facility to adapt to new environmental standard. In Table 2 and Table 3, we present several characteristic data of emission control technologies.

As for SOx emission control, we use the most popular technology of flue gas desulfurization which is classified into seven categories according to flue gas treatment capacity and SOx concentration. As for NOx emission control, we introduced selective catalytic reduction (SCR) and low NOx burner (LNB), and those two technologies are further classified into nine categories according to NOx treatment capacity, NOx concentration, and types of burner. In the MARKAL run the most appropriate combination of the categories is selected, considering the level of flue gas treatment, SOx and NOx concentration in it, capacity share of flue gas treatment equipment actually installed, future possibility of installation of it, etc..

As for emission control in transportation sector, where NOx emission shares a major part, we do not treat emission control tecnology indepently. The reason why we can not help taking such an approach is due to the difficulty of cost evalution, i.e. discrimination of cost for emission control system (e.g. EGR, 3 way catalytic conversion, engine modification, etc.) is in general difficult, even though some part is possible. Therefore, we have taken such an approach for the transportation sector to estimate additional improvement of emission factor and cost increase possibly realized in the future.

The kinds of environmental emissions in the RES are SOx, NOx, CO_2 and radioactivity. The emission factors of each technology are exemplified in Table 4. The emission factors of fixed sources are prepared from the mean value of the 1985 statistical data. Therefore, the numerals can be understood to present the emission to the ambient air from the actually operating flue gas treatment equipment. As for the emission factor of moving sources such as automobiles, ships, and airplanes, we used the emission data compiled by the Japanese Environmental Agency and the Tokyo Metropolitan Research Institute for Environmental Protection. Both SOx emission from the moving sources and CO_2 emission from fossil fuel burning are estimated from the contents of sulfur and carbon in respective fuels.

2.4 Analytical Models and Data Base

Two kinds of analytical models have been employed for this energy environment analysis as shown in Fig. 3. One is the energy system optimization model MARKAL, which was developed through the international cooperative work under IEA/ETSAP. MARKAL has a very flexible framework of energy system modelling, however, we have made two major modifications, i.e. introduction of tradeoff function between system cost and environmental emission ESLOPE(N) and distinction of technology capacity with respect to emission control as described above.

The other model to be employed for the analysis is the multi-sectoral input-output analysis mopdel E-I/O(TRANS). Since detailed description of this model was given in the paper presented in the ETSAP-FEEST meeting at IIASA [5] , the outline only is given below. E-I/O(TRANS) consists of the economy submodel and the energy submodel. The former comprises the I/O analysis module incorporating cost share functions of transcendental logarithmic type for 27 industrial sectors and the macro economy module simulating the economic cycle; production-income distribution-consumption and saving-investment-production. The latter comprises the energy submodel-1, which determines investment, import, and factor inputs of energy sectors based on the information on optimized energy system, and the energy submodel-2 to estimate future technology costs utilizing input price deflators.

The technology data is an essential part of the analytical tool. The data on technical performances and costs have been established for all energy technologies and abatement technologies shown in Fig. 1 and Fig. 2. Here, major part of the data on non-nuclear technolgies are based on the effort by the Electrotechnical Laboratory [6]. The emission data and the data on abatement technologies are based on the technical resources and experiences of the Institute of Behavioral Sciences. The specific technology data required for the analysis by E-I/O (TRANS) are capital coefficients and O&M coefficients, i.e. the information on relative inputs of goods and services from industries for contruction, operation, and maintenance of energy facilities. These data are estimated based on the detailed information on investment and O&M costs.

3. Scenario Analysis

3.1 Scenario Definition

The time interval for scenario analysis is a 45 years period starting from 1985 and ending at 2025. This time interval is not

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3. Scenario Analysis

3.1 Scenario Definition

The time interval for scenario analysis is a 45 years period starting from 1985 and ending at 2025. This time interval is not so enough long for global environmental analysis. On the other hand, it can not be seen so short when we are thinking about changes of our socio-economical and/or industrial structure. Rather, it is appropriate for us to consider this time interval as a transition period from an existing system to a new generation system.

The transition period can also be considered as the time interval where a new frontier of value concept and technology is making competition with the existing one to seek their opportunity. From this reason, some structural changes can be anticipated. For the analysis of such change, we can consider an application of a simulation method. However, a simulation method is generally inclined to be managed severely by a technically fixed frame, even though it has an advantage of deductive ability based on historical trend.

As a contrary approach, we can use an optimization method. This method has in general a normative analytical nature, and employs two different kinds of functional relation, i.e. constraint relations which are treated possibly as endogeneously defined relations and/or exogeneouly given ones and the second one being a system evaluation index, in other words, objective function, and makes a system optimize with respects to the objective function which is maximized or minimized under given constraints. As this method having normative nature, it is the most appropriate for scenario analysis.

As scenario indicators, we select the following set D: D={GDP growth rate, fuel price, crude steel production, ethylene production, cement production, paper and board production, floor area, transportation activities measured by ton·Km and man·Km}. As reference scenarios, we introduce the following two; the scenario HD/LP representing high GDP and low fuel price, and the scenario LD/HP representing low GDP and high fuel price. Fuel price scenarios for the analysis are presented in Fig. 4. In Table 5, we show scenario indicators of the set D for the scenario LD/HP and HD/LP respectively. As additional scenarios for sensitivity analysis we further introduce the following two; i.e. (i) acceleration of synthetic fuel production from coal by non-nuclear existing technology, and accelerating installation of the IES which aims at complementary use of fossil fuel and nuclear energy to mitigate the problems associated with fossil fuel resource and environmental emission, (ii) CO_2 increasing shock when nuclear installation is suspended.

Table 6 shows the MARKAL run cases, which are grouped into three different blocks, i.e. the first block for trade-off analysis between security S (here cummulative imported oil) and discounted system cost C, the second block for trade-off analysis between environmental emission E (weighted average of SOx, NOx, CO emission) and discounted system cost C, and the third block for specific analysis on reducing CO_2 emission.

3.2 Scenario Evaluation Index

For evaluation of scenario, we will introduce scenario evaluation indices as shown in Table 7. Especially, in energy environmental analysis, the fraction of unit primary energy consumption to environmental emission EEM/PES as well as the fraction of unit GDP to environmental emission EEM/GDP become important indices. If we can estimate the upper limits and the lower limits of the index EEM/PES, EEM/GDP by any way, we are able to calculate environmental emission for any level of GDP and primary energy consumption utilizing PES/GDP and the above indices.

Further, if we wish to evaluate the effect of emission reduction from view points of primary energy supply as well as of system cost, we may need noticing a marginal price. Such marginal price can be estimated from the slope on the tradeoff curve between the environmental emission and the discounted system cost. Through comparison of the slope, we can derive the necessary cost for reducing unit amount of environmental emission. We will observe such quantity also in scenario evaluation.

3.3 Results on Reference Scenario

Two sets of energy systems are prepared in order to analyze reference scenarios; with and without emission control technologies for future reduction of environmental emissions. In the system "with control", environmental emissions are reduced through fuel processing, introduction of control technologies, fuel switching, and technology substitution. While in the system "without control", emissions are reduced without use of control technologies. The results of the analysis for cases shown in Table 6 are summarized below.

(1) Energy Demand and Supply

The structure of primary energy supply and the fuel mix of final energy consumption are shown in Fig. 5 and Fig. 6, respectively, for the representative analytical cases. At present oil shares still major part of primary energy supply in Japan. Several years ago, when the situation of demand and supply of oil was quite tight, the future projection of oil price was generally very pessimistic. Accordingly, it was expected that oil would be substituted easily simply by economical reasons.

Compared with the price projections in those days, the present projection expects quite modest growth of future oil price. The results on the primary energy supply strongly reflects this. In the scenario HD/LP, most of the P-E tradeoff cases require present level of oil import up to the year 2010. Coal liquefaction can have economic advantage only after that time. On the other hand, in the scenario LD/HP, the reduction of oil consumption starts in earlier dates, though it proceeds rather slowly.

Natural gas is hardly regarded as a substitute of oil from an economical viewpoint, since it is imported as LNG and the price of it is now linked to the oil price. The results of analysis show the very low contribution in the P case. While, from the viewpoint of environmental emission, natural gas has the advantage of lowest sulfur content among fossil energy resources.

Thus, in the most cases reducing environmental emissions, it is utilized to its upper limit given exogenously.

Nuclear energy is advantageous in both economical and environmental aspects, so that it is introduced fully in almost all scenarios and cases. Renewable energy, generally favorable from an environmental viewpoint, is introduced largely in those cases controlling environmental emissions strictly. The share of it in total primary energy supply reaches 16% in the year 2025 in the case E4 of the scenario HD/LP.

Coal takes a key role in the P-S tradeoff cases, however, its role reduces drastically with increasing control of environmental emissions despite that the reference energy system incorporates technologies for clean uses of coal such as coal gasification, liquefaction, IGCC, and flue gas desulfurization. Conclusion here would be that expansion of coal utilization is hardly compatible with the current subject of reducing environmental emissions.

In the final energy consumption, share of electricity increases with time in all scenarios and cases. It increases to 27% in the year 2025 in the P case of the HD/LP scenario compared with 20% at present. The share becomes higher in both cases with reducing emissions and decreasing oil imports. The outstanding feature of the fuel mix in the P-S tradeoff cases is drastic reduction in the use of liquid fuels. This result is direct reflection of cutting oil imports. Only the small amount of liquid fuels, most of which is produced by coal liquefaction, is utilized mainly in the transportation sector in the later time periods in this case.

On the other hand reduction in the use of solid fuels is remarkable in the P-E tradeoff cases. The utilization of liquid fuels does not change much from the result in the P case. However both low sulfur and high sulfur heavy fuel oil decreases their shares and light distillates increase to make up for them. The use of gaseous fuels substantially increases as in the P-S tradeoff cases.

(2) Environmental Emission

The emissions of SOx, NOx, CO_2 and REM for each case from the year 1985 to 2025 are shown in Fig. 7 and Fig. 8. In P case, the emissions of NOx and CO_2 increase gradually, but that of SOx increase rapidly. The reason of such results is that low price and high sulfur coal and oil are consumed actively. On the contrary, in SP case the emissions of SOx, NOx, and CO_2 decrease because oil is substituted by LNG, nuclear, and renewables. Especially SOx reduction becomes outstanding.

We can observe following results from these figures. By fuel switching and technology substitution we can reduce SOx emission in the year 2025 to 67% (E1 case) 33% (E4 case) of the level in the year 1985, but NOx emission can hardly be reduced to the same level of SOx emission but to 80% (E1 case) - 57% (E4 case). After the year 1985, with the installation of control technologies such as FGD (flue gas desulfurization), SCR (selective catalytic reduction), LNB (low NOx burner), we can reduce SOx and NOx emission to the level 21% and 38% (E4 case), respectively.

The CO_2 emission in the year 2025 is at about 70% level of present emission level in emission minimum case. This result implies the 60% reduction of CO_2 emission per unit amount of useful energy consumed. The reduction is made mainly through the expanded use of nuclear and renewable energy. Although it is beyond the scope of this study to analyze the implication of the above reduction level in relation to the greehouse effect, it can be said that the possible reduction of CO_2 emission is, as compared with that of SOx or NOx emission, quite limitted within the time horizon of this analysis.

Fig. 9 shows the yearly changes of SOx and NOx emission by technology categories. In the "without control" case (P, SP case), SOx emission from electricity generation technologies as well as from enduse technologies in industry sector takes a large share in total SOx emission. While, NOx emissions from these technology categories are not so large as SOx emission. Transportation sector is most responsible for NOx emission with the share 40% of total emission.

In the "with control " case, SOx emission from transportation sector is as much as that in P or SP case, because amounts of SOx emission is in proportion to sulfur contents of fuel and its content is generally very low, so that countermeasures are not always taken. The emission reduction of SOx in electric power generating sector is remarkable, because large scale emission reduction technology such as FGD or SCR can be easily employed in this sector. On the other hand the reduction of NOx emission is remarkable in transportation and fuel conversion sectors. Such results are due to the improvement of emission control technologies, for instances, engine modification, catalytic converter (3 way converter), etc.. In industrial sector NOx reduction does not show the steady progress, because there exist many small scale plants for which the large scale FGD and/or SCR are not applicable.

(3) Technology Configuration

The comparison of electricity generating capacity in P, SP and E4 (with and without control) cases is shown in Fig. 10 for the HD/LP scenario. From these figures, we can observe the followings: Oil fired electric power disappears by the year 2015 in all cases, but if we investigate in detail, we can see the active operation of low sulfur oil fired power in the emission reduction case with fuel switching (E4 without control). Also in the behavior of gas fired and coal fired power plant, we can notice several interesting points, i.e. coal fired plant plays the leading role in electric power genaration from the years 2005 - 2010 in P case, but in SP case, gas fired plant expands its capacity to the scale as large as that of coal plant. However, in the case of E4, coal fired plant, which emits rather large amounts of SOx and NOx, is substituted by gas fired plant, and a barely remaining of coal fired plant is limitted to the type of the integrated coal gasification combined cycle (IGCC). In any case nuclear power is installed almost to its upper bound. Renewable electric power, including geothermal power, is installed less in the case without control than in the case with control, because of high sulfur emission of the geothermal power.

The yearly change of coal utilization in P, SP and E4 cases are shown in Fig. 11. In P and SP case, the amounts of coal utilization increase continuously especially in liquefaction in order to substitute oil. But liquified coal is not so clean as petroleum products that coal liquefaction technology disappears in emission control case (E4 case). As already mentioned above, for the purpose of electricity generation, coal is not utilized except in IGCC. On the other hand, coal gasification technologies are introduced more easily than liquefaction, because desufurization or denitrification of gas is generally easier than for liquid fuels. The utilization of coaking coal is continueing for iron reduction, because reducing gas by VHTR is not introduced in any case.

Fig. 12 presents the installed capacity of IES technologies which use high temperature nuclear heat. The figure indicates us the facts that among hydrogen production technologies, methane-steam reformer is introduced in almost all cases but thermochemical hydrogen production is introduced only in E1 case. Both high temperature electrolysis and reducing gas production are not introduced in any case. Methane-steam reformer produce clean hydrogen from fossil fuel such as synthetic gas or LNG by applying nuchear heat. By this way, fossil fuel and nuclear heat help each other complementarily. Methanol synthesis from synthetic gas and gasoline synthesis from methanol are introduced in SP case considerably, but disappear in emission control cases. Thermochemical heat pipe is also introduced in many cases.

(4) Cost Effectiveness

The P-S tradeoff curve and the P-E tradeoff curves have been derived for the scenario HD/LP as shown in Fig. 13 and in Fig. 14, respectively. The both figures are represented in terms of the system cost discounted back to the present value. It is also noted that the figure for the P-S tradeoff curve has additionally the points of P-E tradeoff cases and the figure for the P-E tradeoff curve has additionally the points of P-S tradeoff cases.

In the P-S tradeoff cases, the SP case shows the minimum amount of oil imports corresponding to 52% of the amount in the P case. The increase in the discounted system cost required for this is 9% (12% in terms of non-discounted system cost). Fig. 14 indicates that environmental emissions are also reduced substantially in the SP case. This is because, in addition to the expanded uses of nuclear and renewable energy, oil is substituted by natural gas rather than coal in this case because of the upper limit for imported coal.

Among the P-E tradeoff cases, the E4 case shows the reduction of SOx by 80%, NOx by 51%, CO_2 by 19% compared with the levels in the P case. The increase in the discounted system cost required for this is 8% (12% in terms of non-discounted system cost). The amount of oil imports in the P-E tradeoff cases changes irregularly, as indicated in Fig. 13, and it exceeds that of the P case in the E2-E4 cases. This result implies that coal must be replaced to some extent by oil in order to make strict control of environmental emissions. Considering that only several years ago the amount of oil imports was together with the total system cost a major indicator to evaluate the role of energy technologies, the emission control in this direction would be hardly acceptable. The above result suggests that strong effort is required towards the clean uses of coal.

3.4 Results on Sensitivity Analysis

The analysis has been made additionally on the RD&D enhanced scenario and the CO_2 shock scenario. In the analysis of the RD&D

scenario, possible amounts of introduction of coal gasification and liquefaction technologies and the IES subsystem have been expanded, and then optimization of the RES has been made with the objective function ESLOPE4. The results are shown in Fig. 15 together with the corresponding results in the reference scenario. This figure indicates that the technologies in the IES subsystem expands their capacity and contribute more on the emission reduction through the increased production of hydrogen and other synthetic fuels. Among coal conversion technologies, steam gasification expands its capacity, however, little or no contribution is observed as for hydrogasification and liquefaction technologies.

In the analysis of the CO_2 shock scenario, it is assumed that nuclear technologies are not introduced after the year 1995 and this can be made up by expanded use of coal under no additional import of oil and natural gas. The analysis has been made for the cases P, E2, and E4 with the results as shown in Fig. 16. This figure indicates that the reduction in SOx and NOx emission can be made substantially without further introduction of nuclear energy, however, CO_2 emission can be hardly reduced without nuclear.

While, the relationships between discounted system cost and environmental emissions are shown in Fig. 17. As compared with the reference scenario, the system cost does not show significant increase due to the assumptions that nuclear is to be substituted solely by coal and future coal prices remain at the assumed levels as the reference scenario regardless of large increase in consumption. Apart from the above assumptions, if we depend on oil and gas to make up for nuclear, the system cost will show much larger increase with a little less increase in CO_2 emission.

Summarizing the aboves, it would be said that nuclear is an attractive option from the economical viewpoint and also for reduction of SOx and NOx emissions, while it is an essential option for reducing CO_2 emission in the longterm.

4. Evaluation of Results

4.1 Energy Utilization

This section summarizes the changes in the structure of final energy consumption, especially the uses of electricity, heat, and synfuels, when environmental emissions are controlled strictly. Fuel mix of final energy consumption is shown in Fig. 18 for the P case and the E4 case of the HD/LP scenario. The share of electricity increases, as described above, with increasing degree of emission control. One reason for it is that development of non-fossil energy is mainly directed for electricity generation. Another reason is that the emission control can be easily practiced when small-scale end-users utilize electricity instead of fossil fuels. The utilization of low, medium temperature heat is expected to contribute on emission reduction from the reason described just above. However, their growth will not be as large as electricity because of practical constraints related to the development of the associated infrastructure and the preference in energy consumption by end-users.

High temperature heat from VHTR is important in the stage of secondary energy production rather than final energy consumption. It is utilized, via hydrogen production, to produce clean and convenient synthetic fuels by reforming fossil fuels. Though its contribution is still limitted within the time horizon of this analysis, it is expected to take a significant role in the long-term "symbiosis" of fossil and nuclear energy.

Direct utilization of solar energy increases steadily with increasing degree of emission control. Under the HD/LP scenario, the share in final energy consumption at the year 2025 reaches around 5% in the E4 case contributing substantially to the reduction of environmental emissions. The only point of this energy seems its availability with comparatively low cost.

Among synthetic fuels important from the environmental viewpoint would be hydrogen and methanol. According to the results of analysis, hydrogen is not economical in the end-use sector. While, it is utilized in furnaces and for transportation when environmental emissions are controlled, with its maximum share as large as 8% of total final energy consumption at the year 2025. Methanol also is not an economical fuel within the time horizon of this analysis. However its use is still quite limitted even when environmental emissions are controlled. Further study would be required on the role of methanol utilization under environmental constraints.

4.2 Technology Utilization

,In this section we will summarize the results on technology utilization focussing especially the role of the IES technologies. The IES subsystem incorporates the technologies mainly to carry out the electric power generation, hydrogen production, methanol synthesis, gasoline synthesis, and process heat supply by applying high-temperature nuclear heat from VHTR and by utilizing fossile fuels and other resources such as water and air. The installed capacities of the representative IES technologies are shown in Fig. 19 and Fig. 20.

The IES technologies take expanded roles in the SP case, as compared with those in the P case, with larger introduction of VHTR and implementation of steam reforming, methanol synthesis, and gasoline synthesis. While in the E1 case, the technologies such as steam turbine with waste heat, CO gas turbine, and helium gas turbine electric power are introduced to substitute oil-fired electric power, therefore, the installed capacities of hydrogen production, methanol synthesis, and gasoline synthesis are reduced compared with the SP case.

In the E4 case, steam reforming and CO shift process are largely introduced to produce hydrogen for the use in industry furnaces, the transportation sector, and the fuel cell. The CO gas from steam reforming is also utilized by the CO gas turbine to produce electric power. The pattern of technology use does not change, though the capacities are expanded, in the additional scenario where technologies are promoted through enhanced R&D.

The above results can be summarized as follows: (i) From the viewpoint of economic performance, the thermochemical heat pipe and the helium gas turbine are competitive. Also the water splitting process UT-3 is comparatively promissing. (ii) In the case where emissions are strictly controlled, the methane steam reforming becomes an important technology. But hydrogen gas produced is not utilized to the methanol synthesis process nor the coal conversion process. Rather it is directly utilized as a substitute of oil products in the enduse sector. (iii) The role of methanol synthesis and its application technologies is quite limitted in the result of this analysis. As described in the previous chapter, it is necessary to make further study on the role of methanol technologies in relevant to the effective utilization of hydrogen produced by high temperature nuclear heat.

4.3 Emission Control

The main methods of emission control, classified here as fuel swithing, technology substitution, and introduction of control technologies, will not be implemented independently to each other. In this sense, the reference scenario is analyzed under the assumption that these methods are employed complementarily except the hypothetical cases where control technologies are not introduced at all.

However the analysis on the role of individual method is also an important subject in this study. Although the possible effect and required cost by each method depend on the conditions it is employed as well as on the extent other methods are implemented, we analyze here on the case where each of the three methods is solely employed to reduce environmental emissions.

In the analysis, the effect of fuel switching is defined as differences in emissions and costs when fuel mix in electricity generation and enduse sector is only changed to reduce emission from that in the P case. The effect of technology substitution, i.e. through application of nuclear and renewable technologies, is approximately evaluated by comparing the results between the two cases where emissions are reduced by both fuel switching and technology substitution (case E4 without control technologies) and where emissions are reduced by only fuel switching. Finally, the effects by control technologies are measured as changes in emissions and costs when control technologies are applied for the energy system optimized in the P case.

Among the results obtained, the possible amount of emission reduction and the increase in the system cost are shown in Fig. 21 and Fig. 22, respectively. Also, cumulative effects on costs and emissions are represented in Fig. 23 together with the P-E tradeoff curves with and without control technologies. The findings on the effect of individual method are summarized below.

Fuel switching has the large effect especially on reducing SOx emissions through the use of LNG and light distillate oils. The possible amount of NOx reduction is not so large as that of SOx reduction because of inevitable emission of thermal NOx more or less generated during combustion processes. The cost increase required is not especially low, though it depends on the relative prices among relevant fossil fuels.

The effect of technology substitution on reducing SOx and NOx emissions is not so large as that of other two methods. This has two reasons. One is that major part of nuclear and renewable technologies is already introduced economically in the cost minimum case and there remains small capacity to be added for this purpose. The other is that we don't have enough options, within the time horizon of this study, to produce non-electric energy by applying nuclear and renewable technologies. The cost increase is quite high compared with the possible amount of SOx and NOx reduction. It can be said that this method should be evaluated rather in terms of the effect on reducing CO_2

emission.

The control technologies can reduce substantially SOx and NOx emissions with relatively low cost. Especially they are essential to reduce NOx emission largely. However there is a practical constraint that they cannot be applied for small scale energy consumers, therefore as shown in Fig. 21 the possible amount of reduction will be saturated.

In addition, the effect of this method depends strongly on the implementation of other methods. In particular the amount of SOx emission further reduced by this method is quite limitted when fuel switching and technology substitution are already implemented. The additional energy required to operate control technologies is not considered in this analysis. If this were taken into account, the cost increase would be larger through increases in primary energy supply and capacity of associated energy technologies.

The above findings can be now summarized as follows. From the viewpoint of reducing SOx and NOx emissions, introduction of control technologies has the highest cost effectiveness. Fuel switching comes next but with greater possibility in the amount of reduction than employing control technologies. The cost effectiveness of technology substitution will be more appropriately evaluated through detailed analysis of its contribution on reducing longterm CO_2 emissions.

5. Conclusion

The energy environment analysis made here is restricted within the frame of routine emissions and the kinds of emissions are limitted in SOx, NOx, CO_2, and radioactivity. However, if we wish to analyze the whole scope of emission, we must include the analysis for accidental emission and expand the kinds of emissions also. Especially concerning accidental emission, we need emission.

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Tradeoff relationship between cost and emission is one of the important subjects in this study. However, its analytical results will take their value first only if the consequences of cost and emission can be evaluated in socio-economy and ecological considerations. To this direction, we hope that our research activity will be promoted.

The followings are our main findings at this moment:

(1) Both SOx and NOx emission can be reduced much by the present art of methods. Among them, abatement technology takes the highest priority and fuel switching and technology substitution follow in this order. For CO_2 reduction, technology substitution such as through nuclear and renewable technologies becomes effective. However, as far as the IES technologies are concerned, their contribution will become significant after the year 2020.

(2) In primary energy supply, nuclear energy is advantageous in both economical and environmental aspects, and renewable energy is introduced largely in case of reducing environmental emission severely. On the other hand, coal is restricted strictly when environmental constraints become severe, even though gasification, liquefaction, IGCC technologies are prefered in security case (i.e. substitution for oil and gas).

(3) In final energy consumption, electricity is prefered much not only from environmental viewpoint but also for the substitution of oil products. Direct heat utilization is also an important option to mitigate SOx, NOx, CO_2 emissions. We must also notice that the fuel mix of the enduse sector is declined to select gaseous fuel. The revealed preferences such as electric car, hydrogen car, etc., are the examples. However, on such results we may need further investigation.

(4) Improvement of fuel and/or energy utilization efficiency will

be one of the important studying subjects in our future energy system. The present analytical results indicate us the fact that both in conversion sector and in enduse sector efficiency improvement is very small because new energy technologies have rather low efficiency. To overcome this disadvantage, the rational energy uses such as employing a co-generation of heat and electricity, heat pump, etc., must be investigated furthermore in detail. Especially, in case of large scale fossil fuel utilization, such consideration may bring us the benefits of fuel resource saving as well as of reducing environmental emissions.

(5) Concerning IES technologies, an example aiming at a fossil-nuclear symbiosis, we can recognize hydrogen as a very important substance in this study. It can serve not only as strong agent for fossil fuel reforming but also as fuel and feed stock directly used at enduse sector. In relation to emission reduction, we have expected a large role on methanol. However, it is introduced only in the security case. On this, we may need a further study.

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Table 1 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 Coal Steam Elc.	20	70	35.2	901.6	38.0	0.51
E06 Coal Advanced Elc.	20	70	44.0 - 48.0	919.6	40.0	0.80
E13 Oil Steam Elc.	20	70	39.1	522.9	22.4	0.16
E21 LWR Elc.	30	70	33.7	1422.	81.6	0.67
E26 LMFBR Elc.	30	70	40.3	1849.	106.0	*3
E31 Hydroelectric	60	45	——	2378.2	83.3	*3
E32 Geothermal Elc.	20	80	——	1812.	72.0	0.08
E4B Solar Photovol.	20	50	——	3056.2 -1439.6	2.3	*3
E9A He Gas Turbine Elc.	30	70	43.0	299.1	14.8	0.38
E9C CO Gas C.C. Elc.	30	80	60.0	688.	40.5	0.18
Process Technology						
S01 Coal Hydrogas.	20	90	85.1	4.80	0.22	0.10
S03 Coal Steam-gas	20	90	83.6	6.92	0.44	0.12
SOE Coal Liq. (Light)	20	90	65.0	35.57 -23.72	1.18 -0.59	0.37 -0.19
SOF Coal Liq. (F-T)	20	90	63.0	16.40	0.55	0.17
SOG Coal Liq. (Heavy)	20	90	70.3	28.90 -19.26	0.91 -0.46	0.29 -0.15
S91 Steam Reform	20	90	95.0	1.89	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	2.96	0.21	0.13
S98 Coal to Red. Gas	20	90	66.0	3.19	0.34	0.07
S9C CO-H_2 Sep.	20	90	89.6	3.95	0.18	0.35
S9D H.T. Electrolysis	20	90	87.3	12.03	0.64	1.16
S9K Methanol Syn.	20	90	88.2	1.43	0.08	0.03
S9M Gasoline Syn.	20	90	81.8	3.17	0.21	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 2 Technical Performances and Costs of SOx Control Technologies

Equipments	SS0	SS1	SS2	SS3	SS4	SS5	SS6
Technology	FGD	FGD	FGD	FGD	FGD	FGD	FGD
Capacity $10^3 Nm^3/H$	1000	500	100	200	100	200	10
Inlet SO_x ppm	500	300	120	400	300	100	250
Removal Eff. %	95	90	90	90	90	90	90
Annual SO_x Input Ton	12,510	3,757	300	2,000	751	351	63
Capital Cost $\$/(kg\ SO_x^*/y)$	3.568	6.534	45.57	4.883	6.503	44.03	44.21
Fixed O&M $\$/(kg\ SO_x^*/y)$	0.141	0.297	0.342	0.103	0.136	0.410	0.163
Variable O&M $\$/kg\ SO_x^*$	0.120	0.254	0.298	0.089	0.119	0.356	0.142
Energy Technology Group	E01 E13 E32 E61 etc.	E14 E15	S1E S2A S2B S06 etc.	I22 I25 I36	I2A I33 I38	I26 I37 IC1 IA2 etc.	R13 RIA R53 R59

* Throughput FGD: Flue Gas Desulfurization

Table 3 Technical Performances and Costs of NOx Control Technologies

Equipments	SN0	SN1	SN2	SN3	SN4	SN5	SN6	SN7	SN8
Technology	SCR	SCR	LNB	SCR	LNB	SCR	SCR	LNB	LNB
Capacity $10^3 Nm^3/H$	1000	1000	500	300	100	200	100	200	10
Inlet NO_x ppm	200	150	150	200	100	300	150	100	150
Removal Eff. %	90	80	35	80	35	80	80	35	35
Annual NO_x Input Ton	3598	2698	1350	1080	180	1080	270	360	27
Capital Cost $/(kg NO_x^*/y)	3.728	5.079	0.468	4.323	0.702	3.012	6.495	0.702	0.959
Fixed O&M $/(kg NO_x^*/y)	0.128	0.170	0.058	0.132	0.087	0.099	0.248	0.087	—
Variable O&M $/kg NO_x^*	0.643	0.857	—	0.656	—	0.495	0.495	—	—
Energy Technology Group	E01 E13 E61	E02 E11	E14 E15 E81 E84	S1E S33 S06 etc.	S2A S2B S30 etc.	I25 I33 IC1 IC2 etc.	I21 I22 I32 I38	I23 I2A I34 IA4 IAB etc.	R13 R15 R1A R53

* Throughput SCR; slective Catalytic Reduction LNB; Low NO_x Burner

Table 4 Emission Coefficients of Main Technologies

Technology			SO_x 10^3 T/PJ	NO_x 10^3 T/PJ	CO_2 10^3 T/PJ	Radiation* rem/PJ
Conversion Technology						
E01	Coal Steam Elc.		0.463	0.194	92.2	—
E06	Coal Advanced Elc.		0.016	0.021	92.2	—
E13	Oil Steam Elc.		0.241	0.085	77.2	—
E82	Gas Steam Elc.		0.000	0.021	54.9	—
E32	Geothermal Elc.		0.349	—	—	—
E81	Gas Turbine Elc.		0.000	0.067	54.9	—
E61	Coal Cogeneration		0.437	0.178	92.2	—
E21	LWR Elc.		—	—	—	0.21
Process Technology						
S01	Coal Hydrogas		0.010	0.017	7.47	—
S03	Coal Steam-gas		0.016	0.029	25.8	—
S06	Coke Oven		0.005	0.009	6.76	—
SOF	Coal Liq. (F-T)		0.029	0.025	32.3	—
S98	Coal to Red. Gas		0.010	—	42.5	—
S2A	Petroleum Refinery		0.002	0.001	1.36	—
S2B	Upgrade Refinery		0.001	0.001	1.00	—
SA4	VHTR (Process Heat)		—	—	—	0.006
Demand Technology						
Industry	I22	Oil Boiler	0.536	0.111	77.2	—
	I25	COM Boiler	0.434	0.151	84.0	—
	I3B	Furnace	0.033	0.101	49.6	—
	IA1	Iron & Steel Melt.	0.039	0.006	92.2	—
	IC1	Cement kiln	0.037	0.360	271.7	—
Residential & Commercial	R12	Space Heating	0.002	0.028	75.1	
	R82	Air Conditioning	0.004	0.044	56.2	—
	R23	Space Heating (House)	0.004	0.018	56.2	—
	R62	Water Heating (House)	0.002	0.028	75.1	—
Transport	T12	Rail way	0.166	1.039	77.1	—
	T41	Automobile	0.004	0.163	77.6	—
	T51	Bus & Truck	0.166	0.539	75.1	—
	T91	Air Craft	0.002	0.314	75.9	—

* Radiation exposure dose

Table 5 Scenario Indicators for Scenario HD/LP and LD/HP

Year Indicator		1985	2000	2020
GDP growth rate (%/y)	$H^{(3)}$		2.9	1.8
	L		2.1	1.2
Price of crude oil ($/GJ)	H	4.46	4.34	6.25
	L	4.46	5.54	9.60
Crude steel production (10^6 t/y)	H	105.3	100.0	106.6
	L	105.3	100.0	100.0
Ethylene production (10^6 t/y)	H	4.23	3.85	3.88
	L	4.23	3.35	1.86
Cement production (10^6 t/y)	H	72.8	73.0	73.0
	L	72.8	65.0	65.0
Paper and board production (10^6 t/y)	H	21.0	26.8	32.7
	L	21.0	26.8	30.6
Floor area (10^6 m^2)	H	1400	1998	2613
	L	1400	1851	2193
Passenger transportation$^{(1)}$ (10^9 person·km/y)	H	489	794	1257
	L	489	627	799
Freight transportation$^{(2)}$ (10^9 t·km/y)	H	206	328	527
	L	206	276	337

Note: (1) Automobile and bus
(2) Truck
(3) H: HD/LP scenario, L: LD/HP scenario

Table 6 Scenarios and Cases for Energy-Environment Analysis

Objective Function(1) / Scenario	P-S Tradeoff			P-E Tradeoff				Minimum CO_2
	P	QP	SP	E1	E2	E4	EP	
Reference Scenarios								
High Demand/Low Price (HD/LP)								
With Control Technologies	X	X	X	X	X	X	X	X
Without Control Technologies				X	X	X	X	
Low Demand/High Price (LD/HP)								
With Control Technologies	X					X		
Additional Scenarios(2)								
R&D Enhanced Scenario						X		
CO_2 Schock Scenario	X				X	X		

Note: (1) Objective Functions:

P : Discounted System Cost
QP: P+7.*S (S: Security)
SP: Minimum P at Minimum S
EP: Minimum P at Minimum E

E_n: P+e(n)·E
where E=SOxEmission+NOxEmission
+0.001*CO_2Emission

e(n)=1. for n=1
5. 2
50. 4

(2) Additional scenarios are studied based on the HD/LP scenario with control technologies.

Table 7 Scenario Evaluation Indices

Case / Index / Year	(Actual)	HD/LP-P		HD/LP-QP		HD/LP-E4		LD/HP-P		Min. CO_2	
	1985	2000	2020	2000	2020	2000	2020	2000	2020	2000	2020
PES/Capita (GJ)	123	137	179	138	178	139	169	130	152	137	173
PES/GDP (GJ/10^6¥)	51.5	41.8	38.5	40.7	38.3	41.0	36.3	43.3	41.2	40.4	37.2
UED/PES (%)	37.9	36.6	35.6	37.5	35.8	37.3	37.8	37.1	35.7	37.8	36.8
IPE/PES (%)	81.9	72.2	62.9	69.8	54.7	70.9	56.1	70.8	57.3	69.6	53.4
SO_x Emis./PES (g/GJ)	90	126	107	108	49	26	16	124	91	73	41
NO_x Emis./PES (g/GJ)	105	96	82	93	60	60	37	92	71	79	65
SO_x Emis./GDP (kg/10^6¥)	4.65	5.26	4.13	4.43	1.90	1.06	0.58	5.38	3.77	2.95	1.52
No_x Emis./GDP (kg/10^6¥)	5.44	4.01	3.18	3.82	2.30	2.47	1.36	3.99	2.95	3.22	2.43

Note
GDP : Gross Domestic Product
PES : Primary Energy Supply
UED : Useful Energy Demand
IPE : Imported Primary Energy

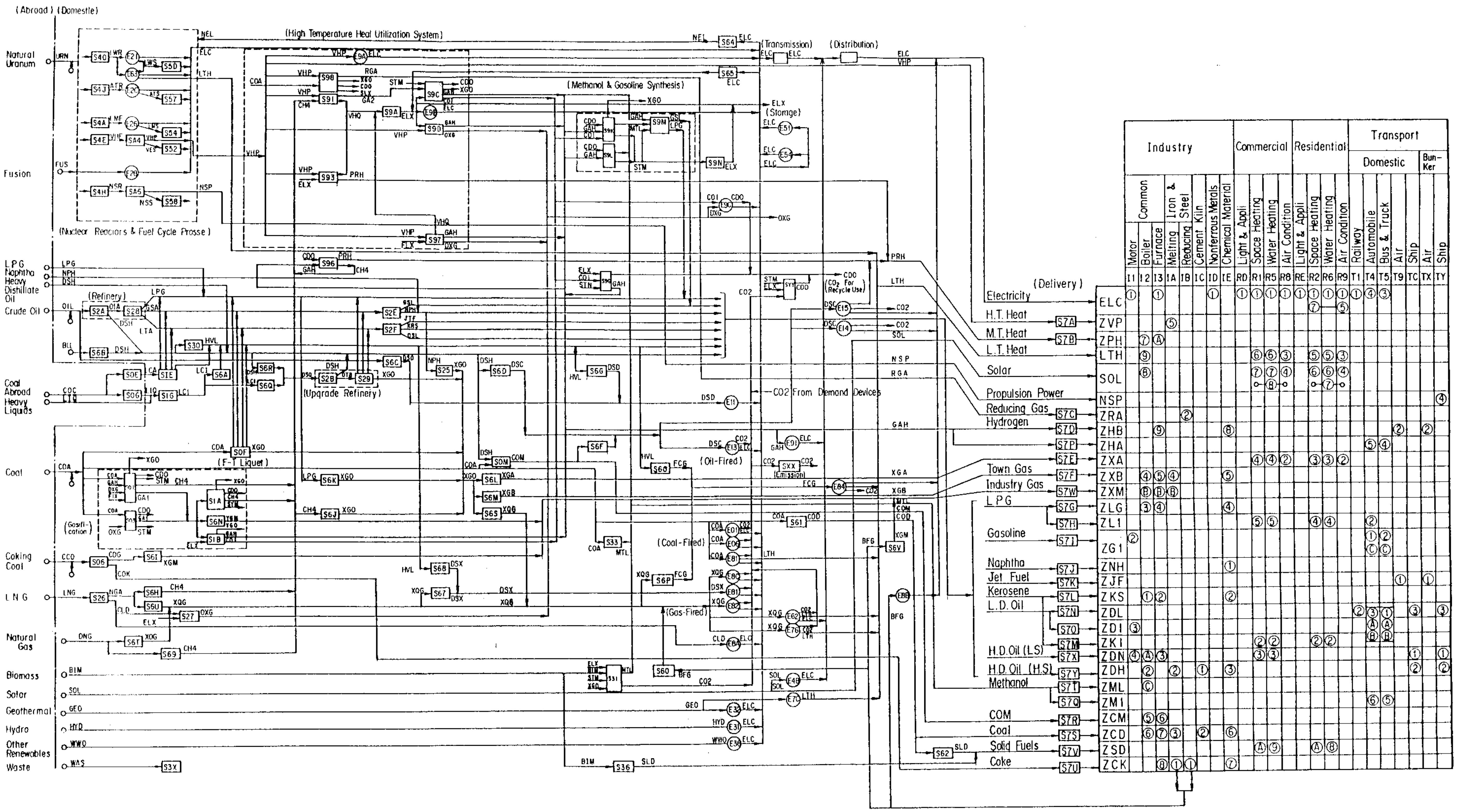
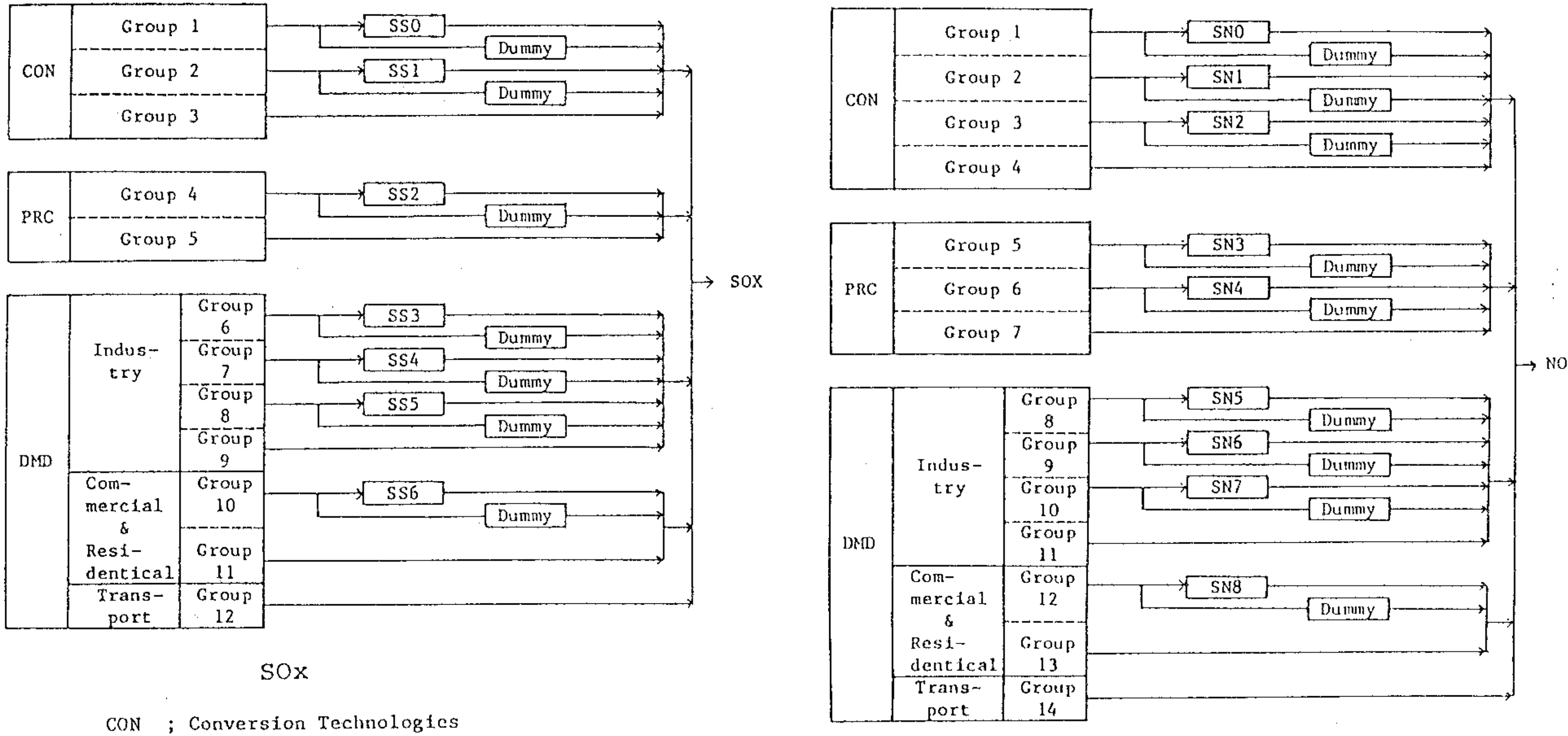


Fig. 1 Structure of Reference Energy System



SOx

NOx

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

Fig. 2 Emission Control Technologies and Their Connection to Energy Technologies

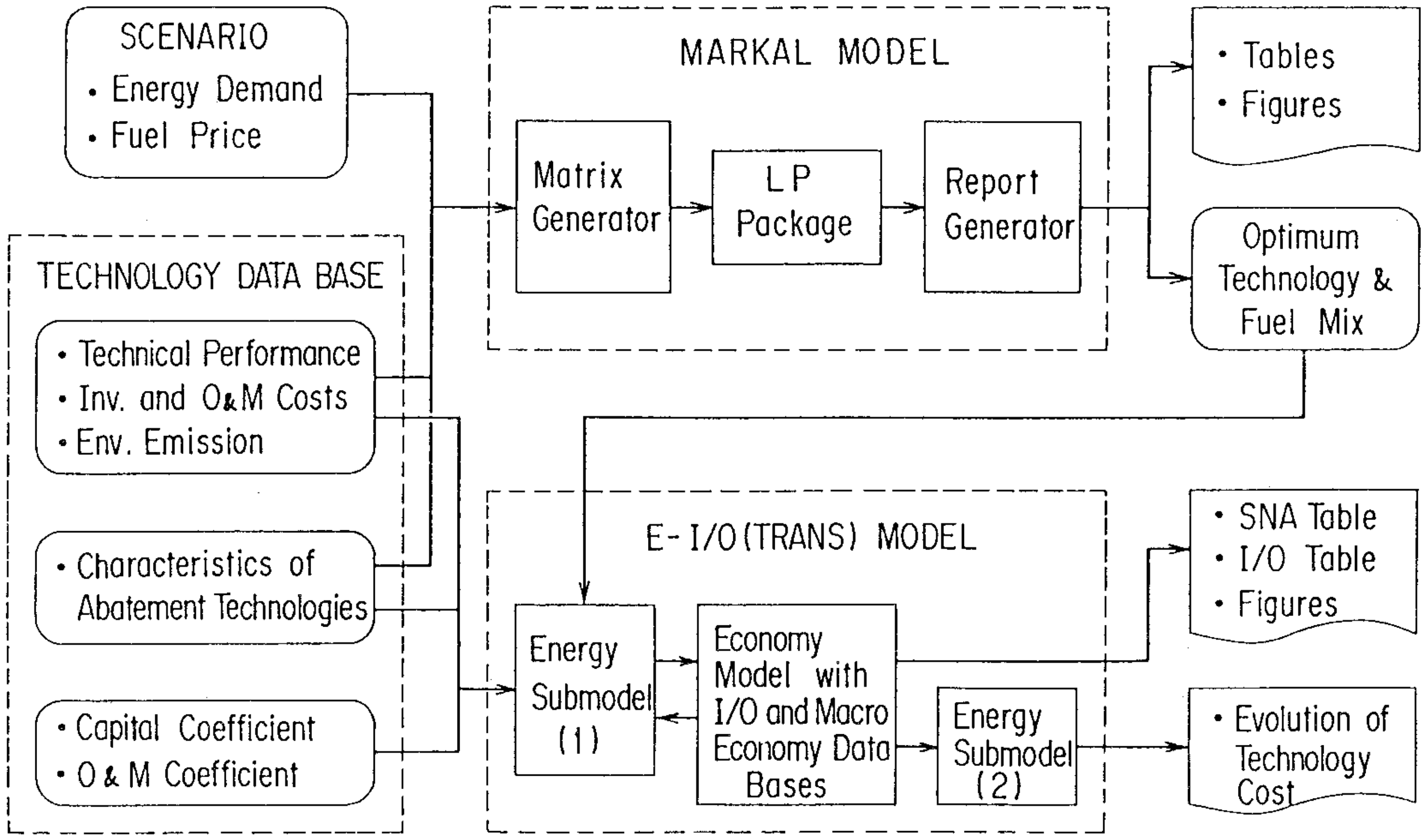


Fig. 3 Models and Data Bases for Energy-Environment Analysis

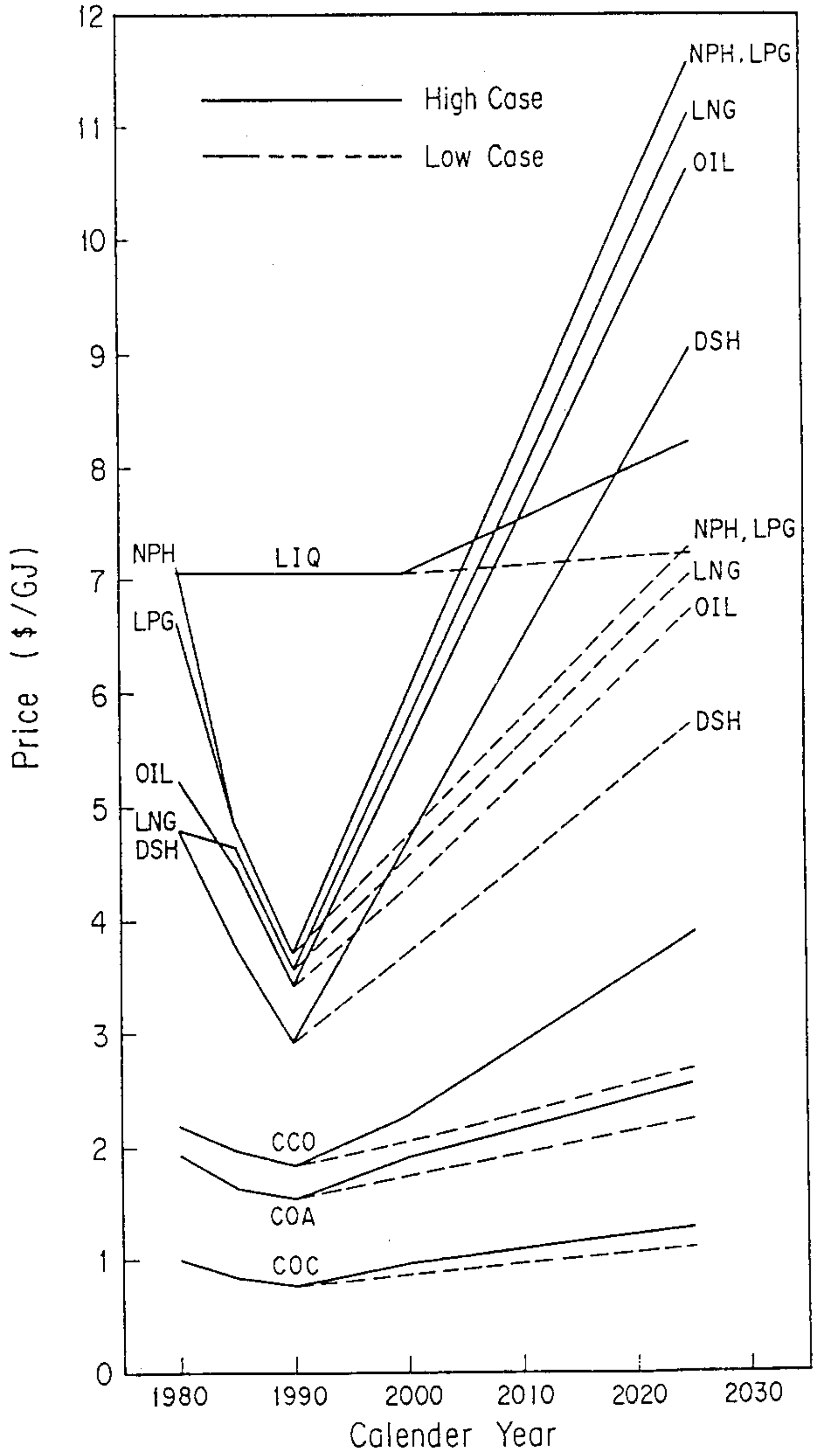


Fig. 4 Fuel Price Scenarios through the Year 2025

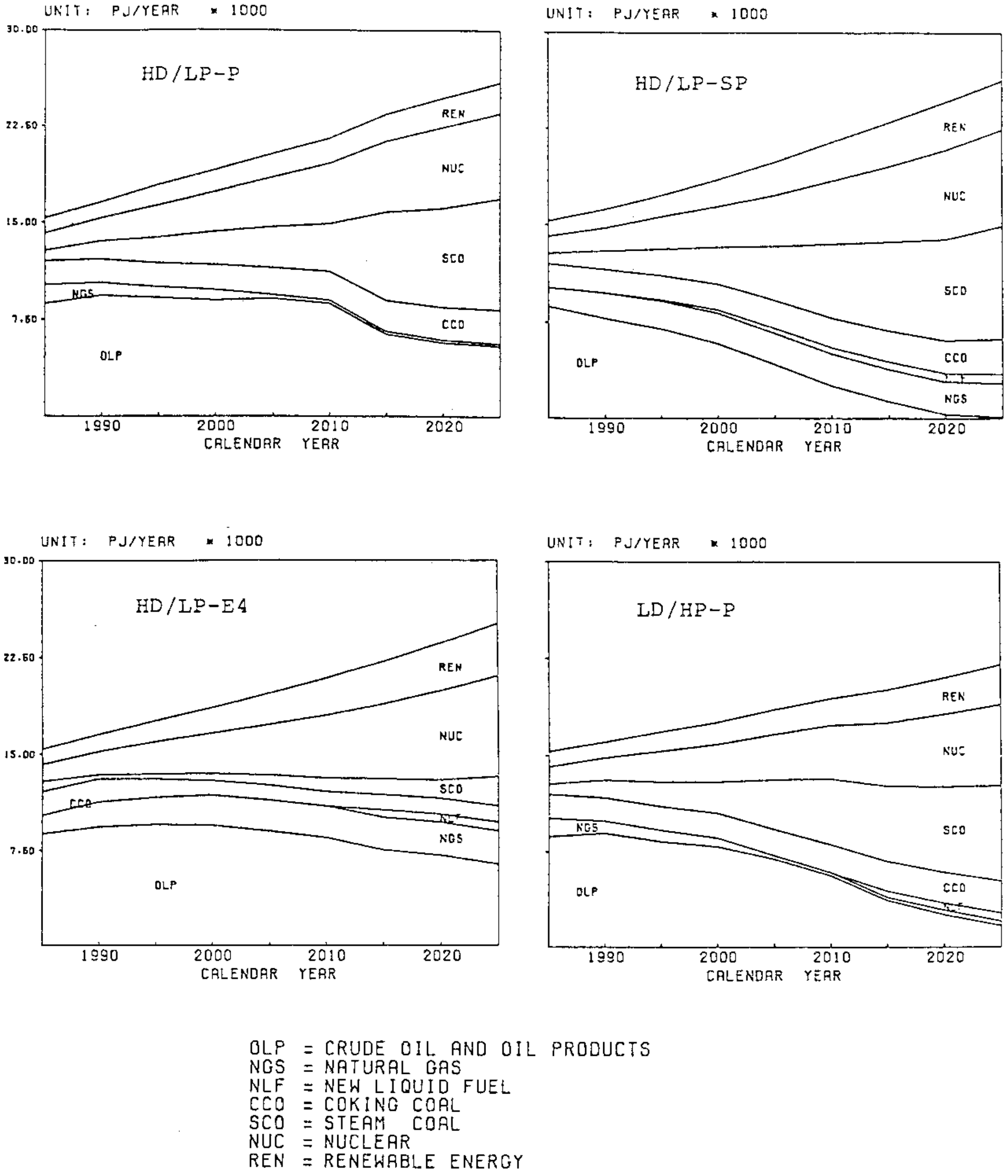


Fig. 5 Primary Energy Supply in Reference Scenario

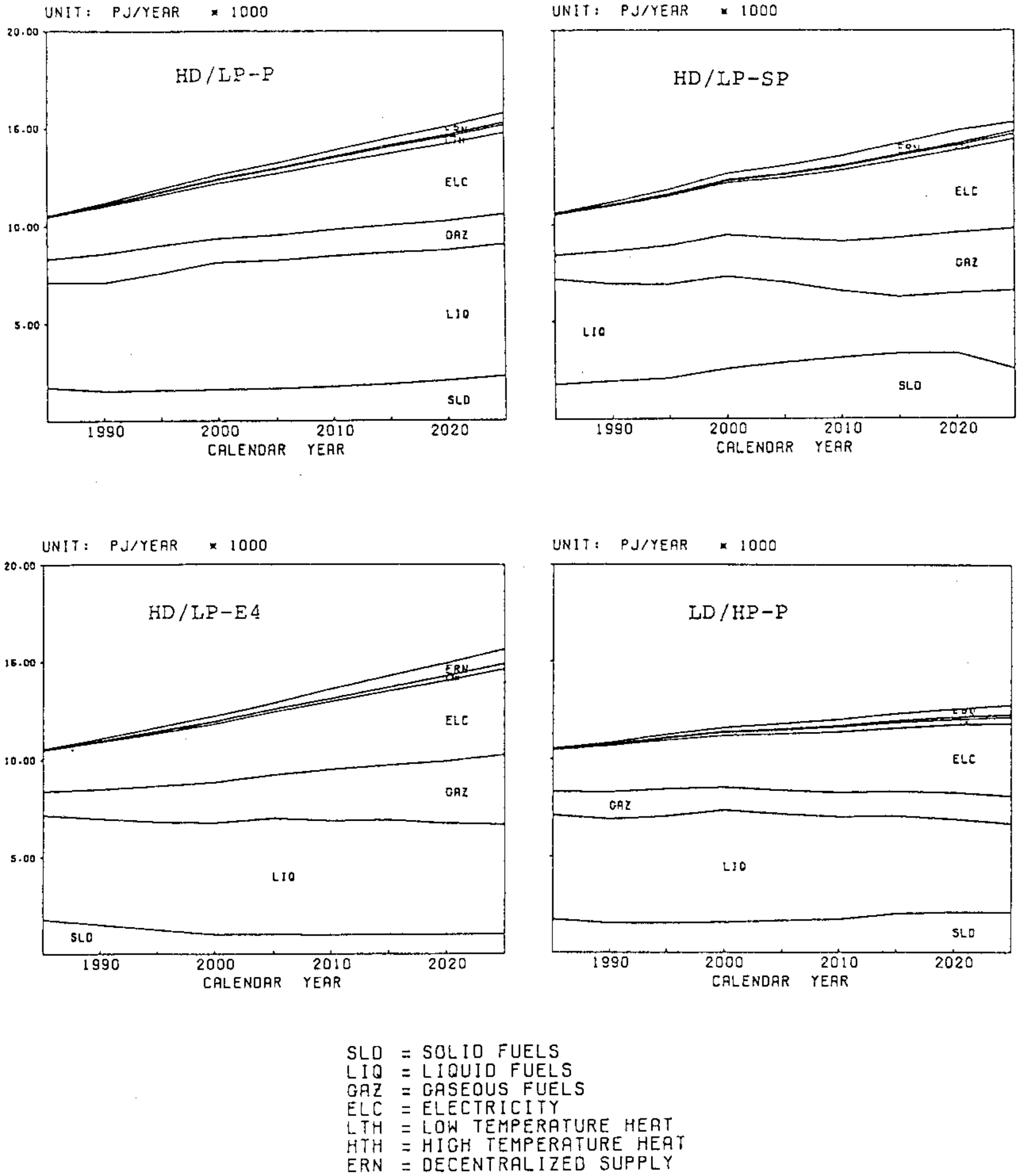
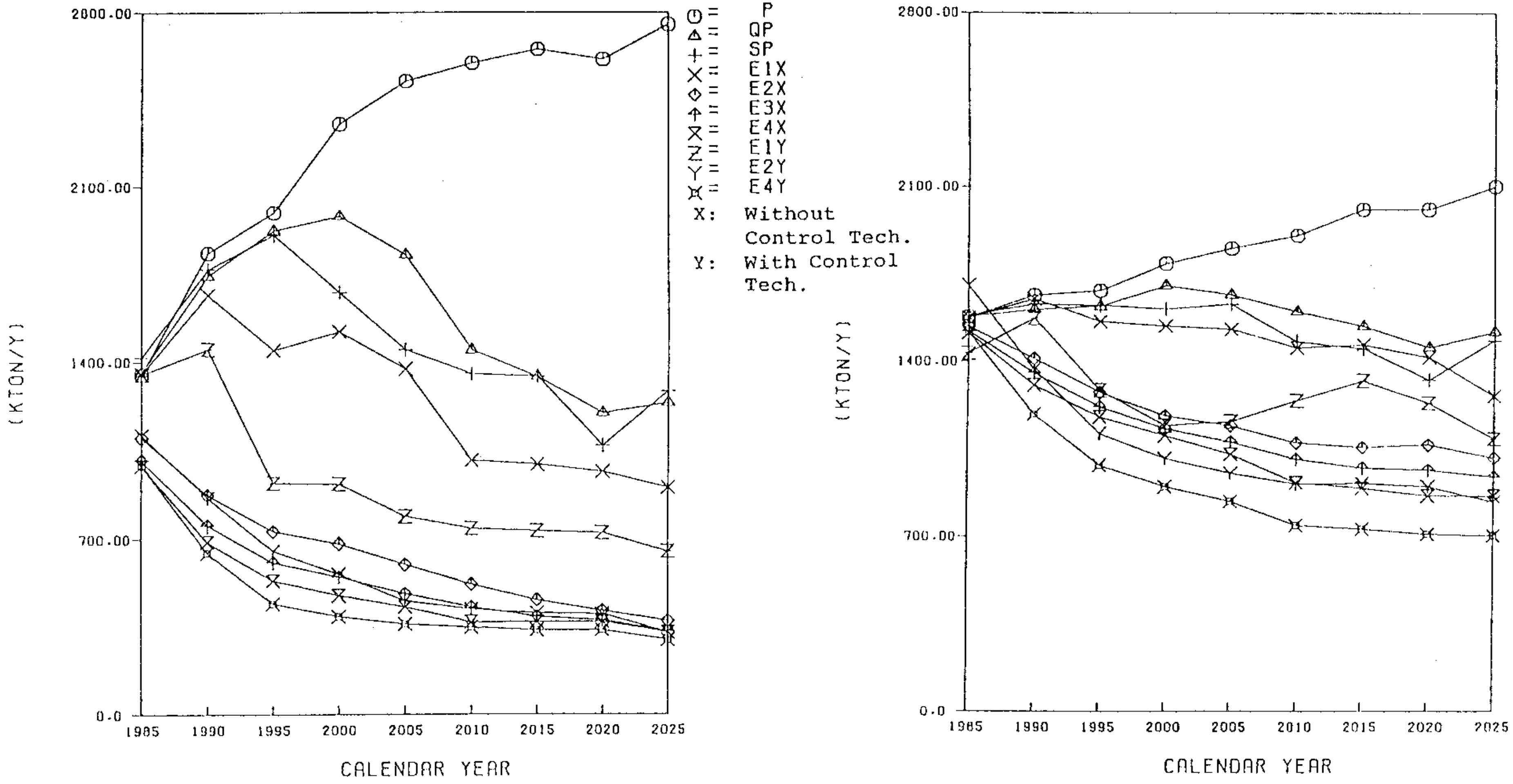


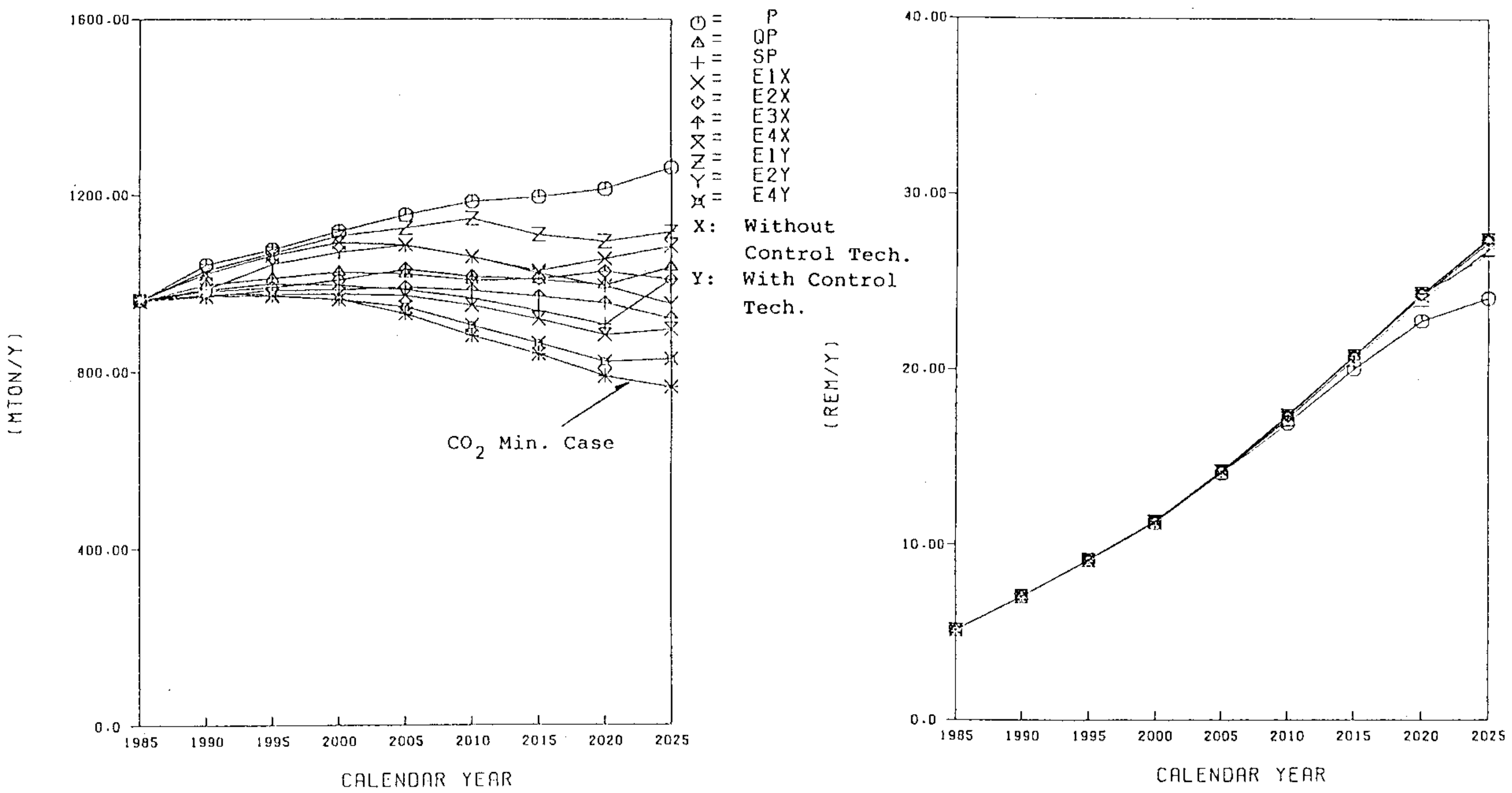
Fig. 6 Final Energy Consumption in Reference Scenario



SOx

NOx

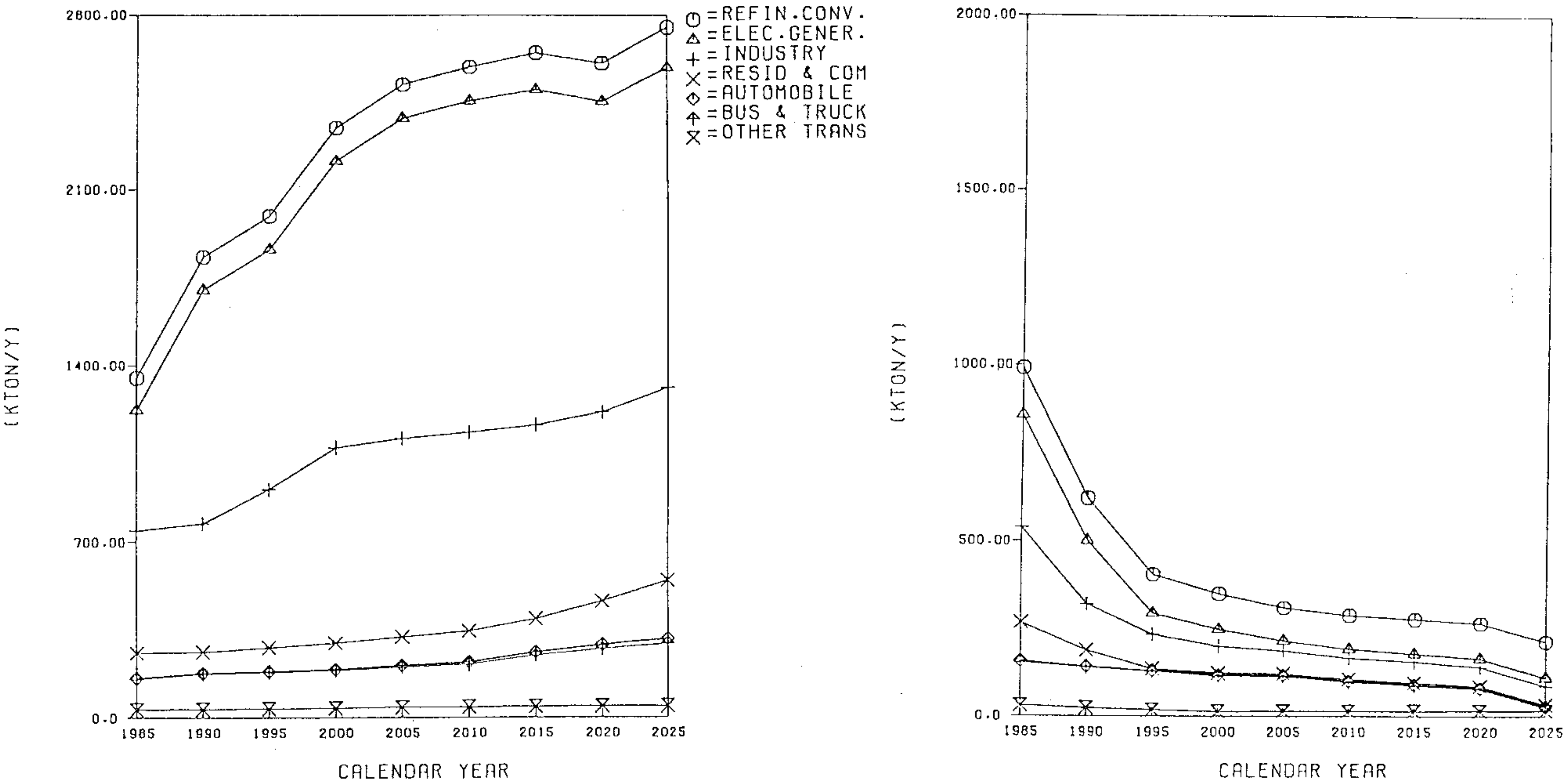
Fig. 7 SOx and NOx Emissions in Reference Scenario



CO_2

Radiation Exposure

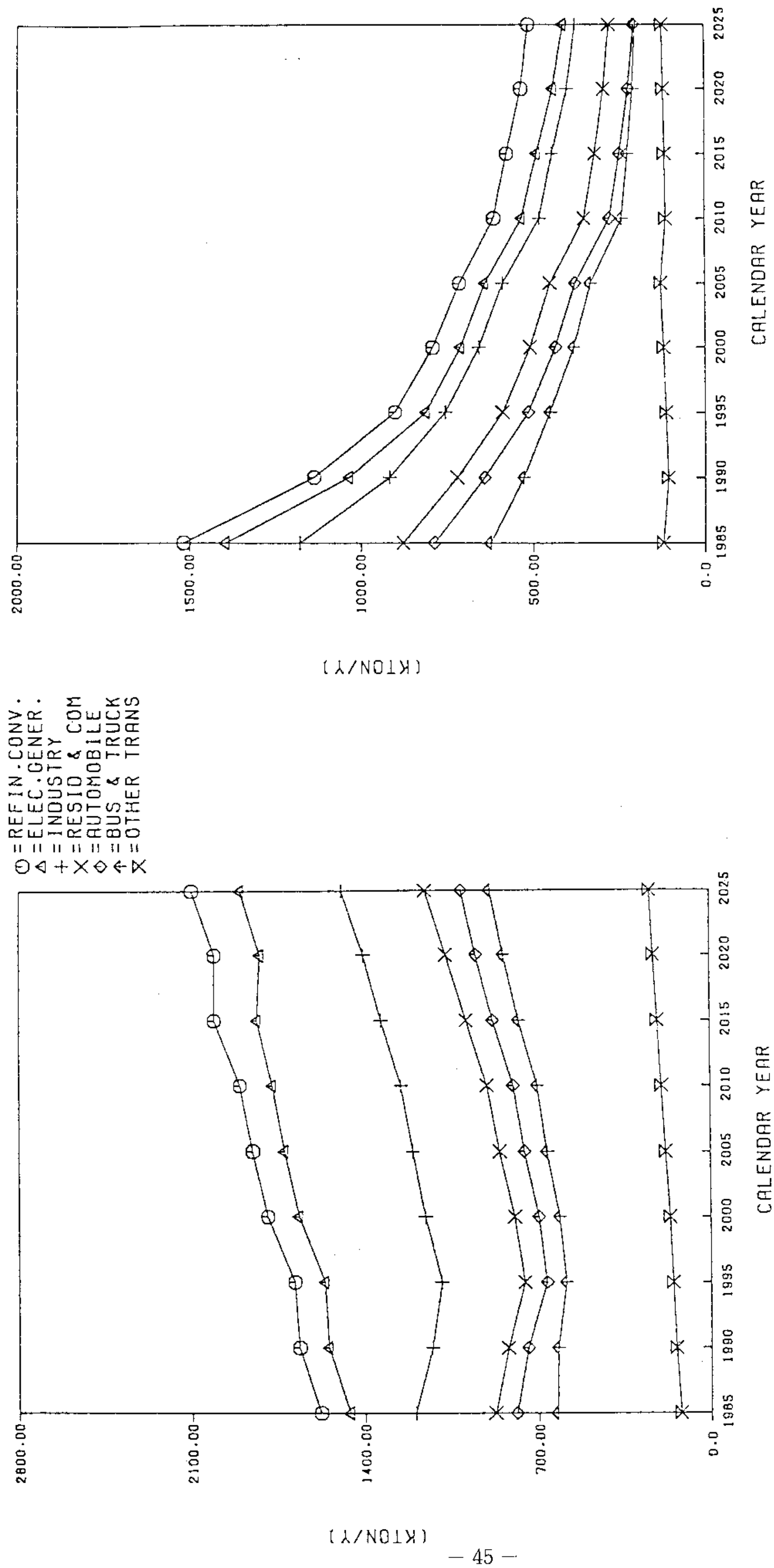
Fig. 8 CO_2 Emissions in Reference Scenario



P Case

E4 Case (With Control Tech.)

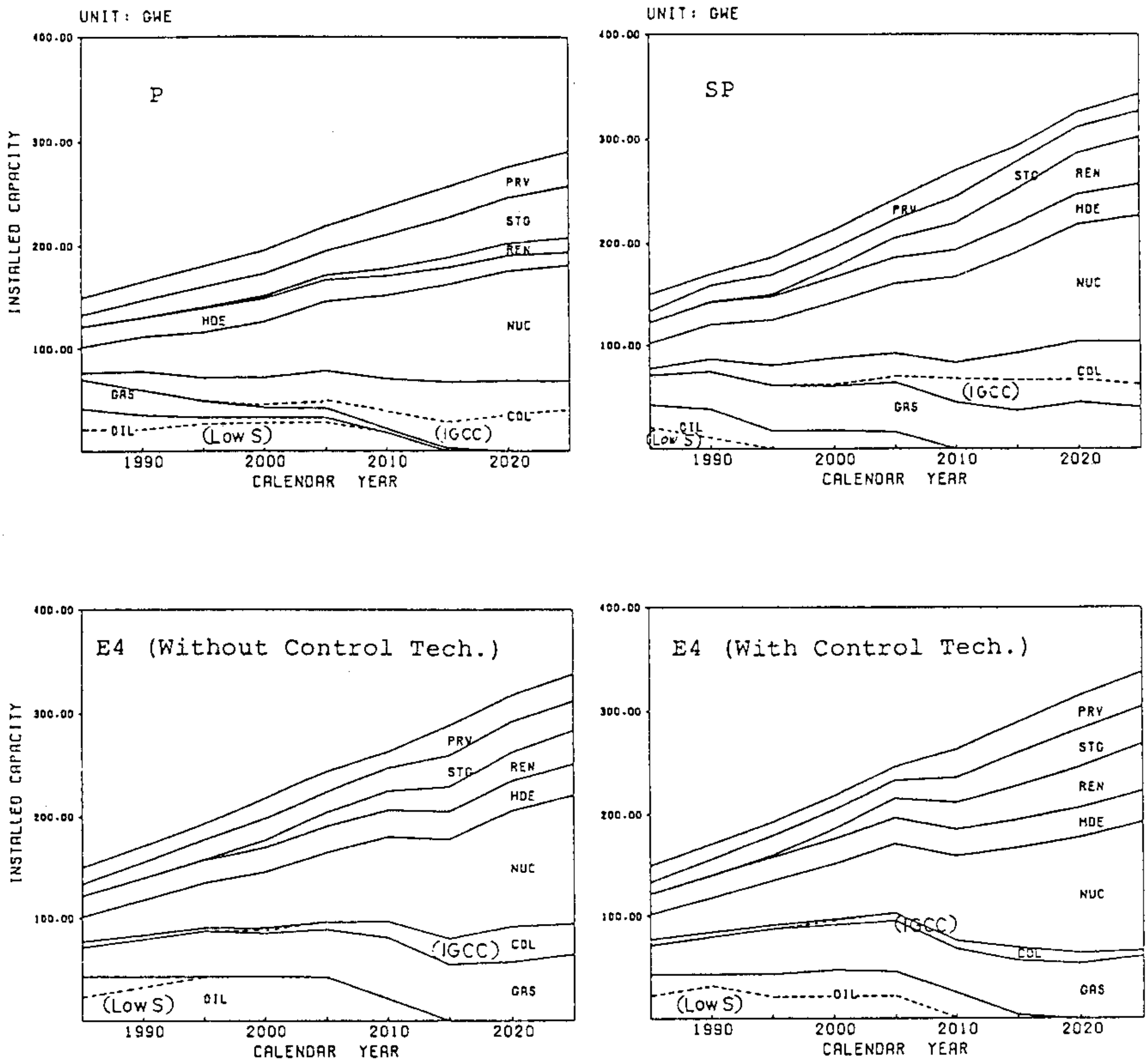
Fig. 9(a) Sectoral Aggregation of SOx Emission



E4 Case (With Control Tech.)

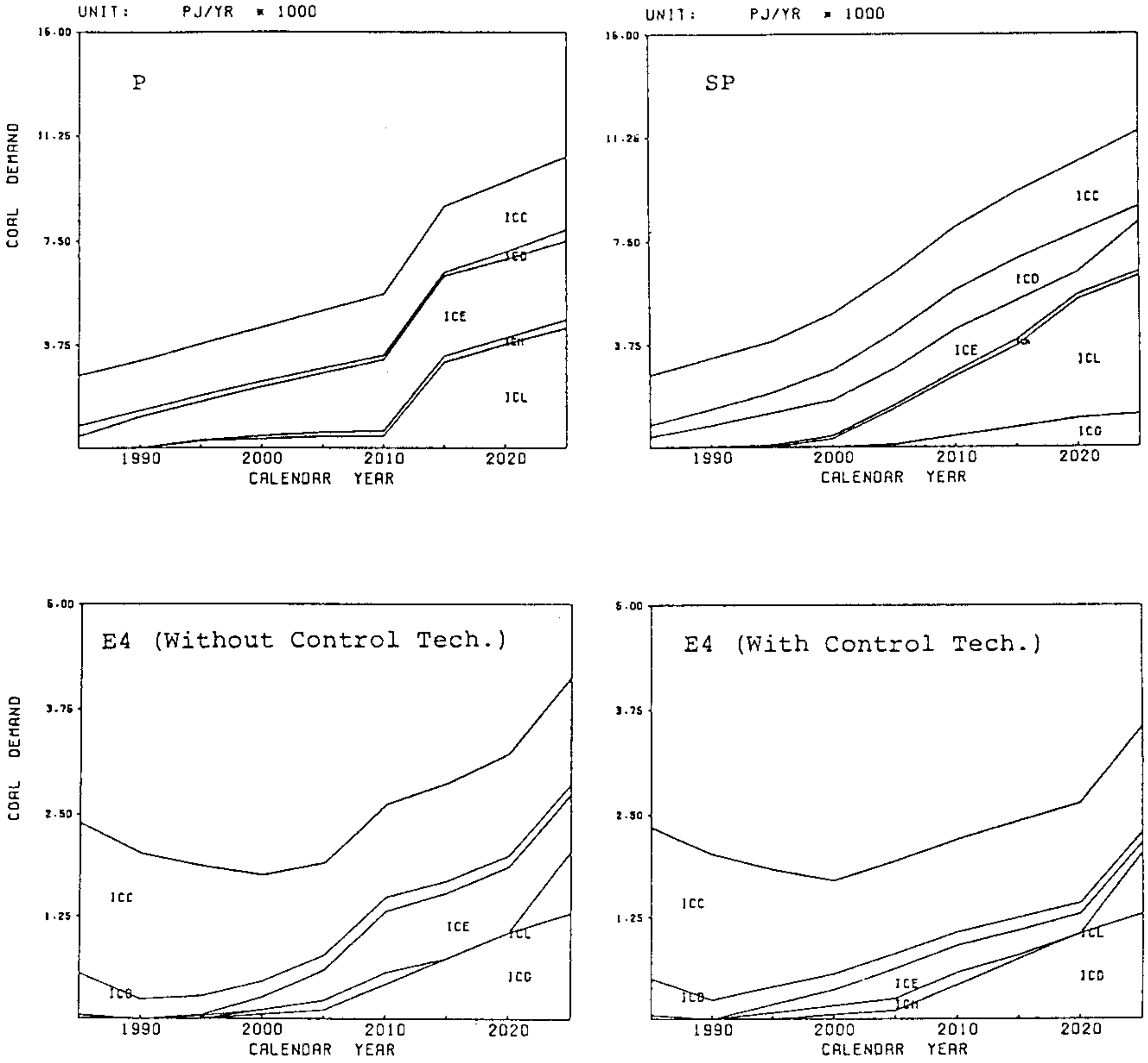
P Case

Fig. 9(b) Sectoral Aggregation of NOx Emission



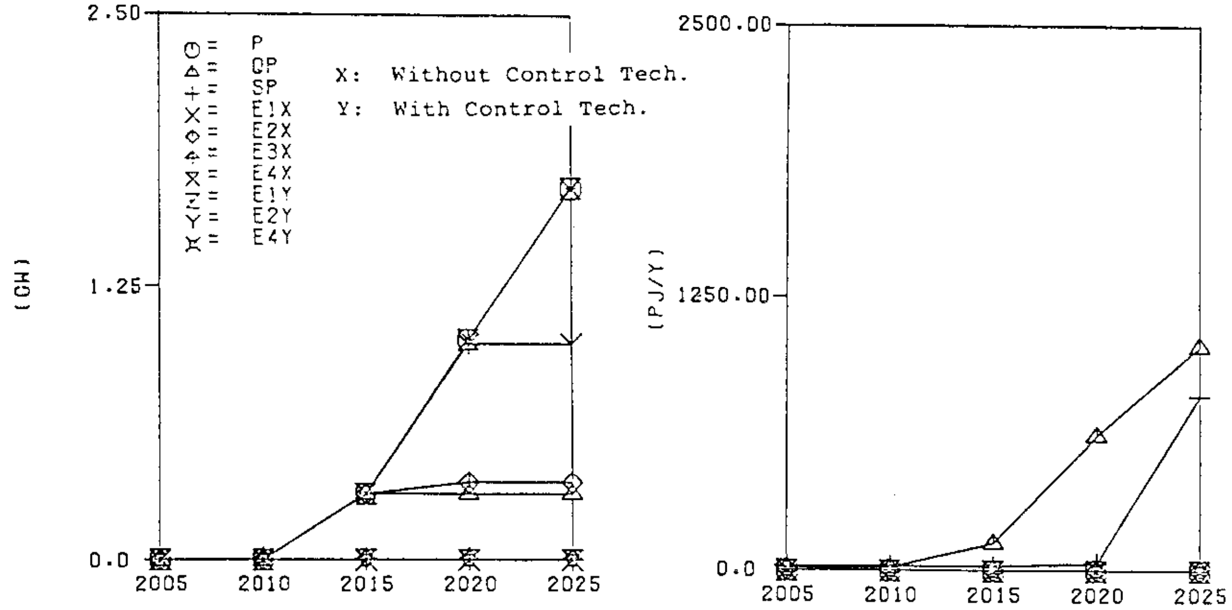
OIL = OIL STEAM ELECTRIC POWER PLANT
GAS = GAS STEAM ELECTRIC POWER PLANT
COL = COAL STEAM ELECTRIC POWER PLANT
NUC = NUCLEAR ELECTRIC POWER PLANT
HDE = HYDRO ELECTRIC POWER PLANT
REN = OTHER RENEWABLE ELECTRIC POWER PLANT
STG = ELECTRIC STORAGE POWER PLANT
PRV = AUTO GENERATION POWER PLANT

Fig. 10 Installed Capasity of Electric Power Plant



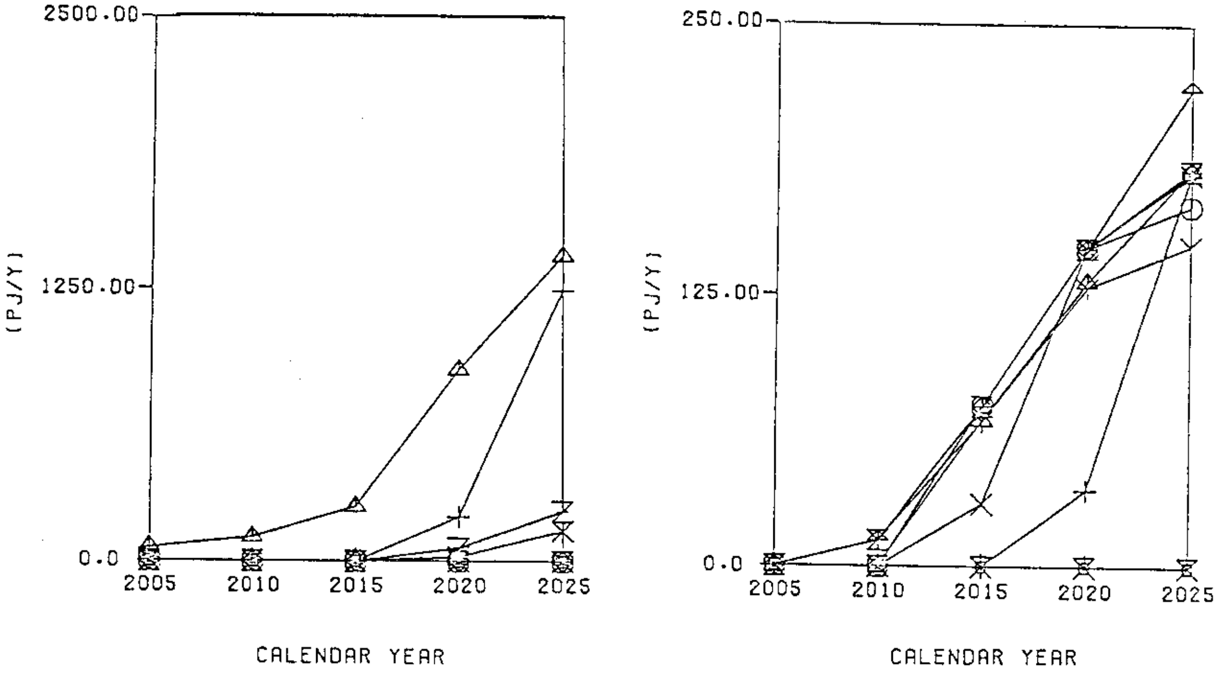
ICG = GASIFICATION
ICL = LIQUEFACTION
ICM = COAL OIL MIXTIRE
ICE = ELECTRIC POWER GENERATION
ICD = DIRECT UTILIZATION
ICC = COKING COAL

Fig. 11 Utilization of Coal



Helium Gas Turbine

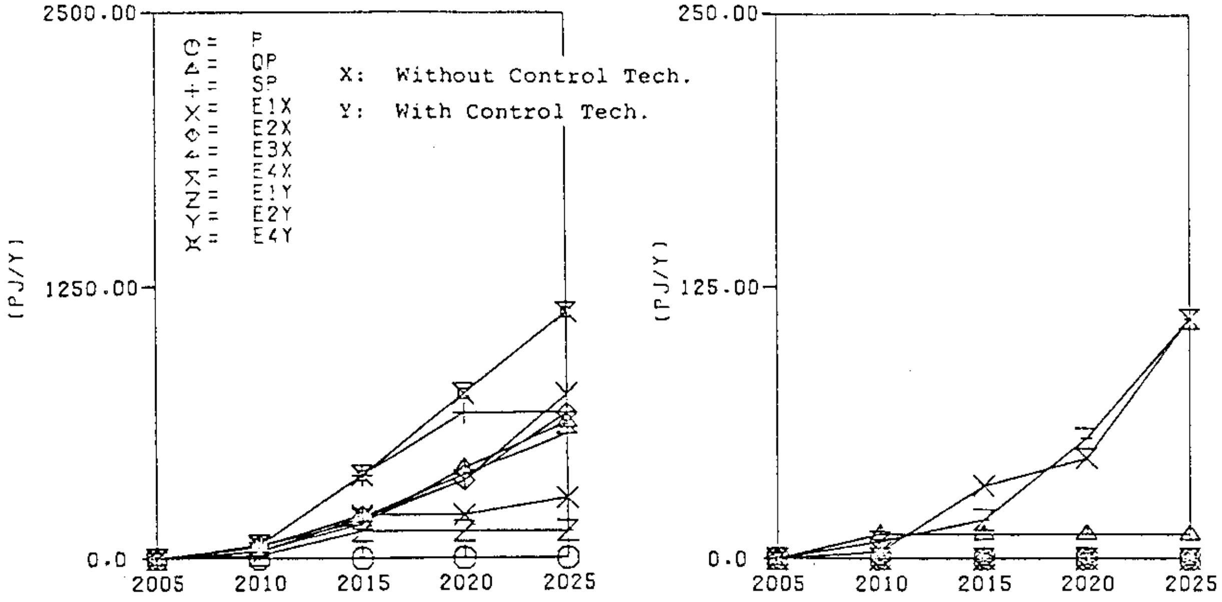
CO-Methanol Production



MTG Gasoline Production

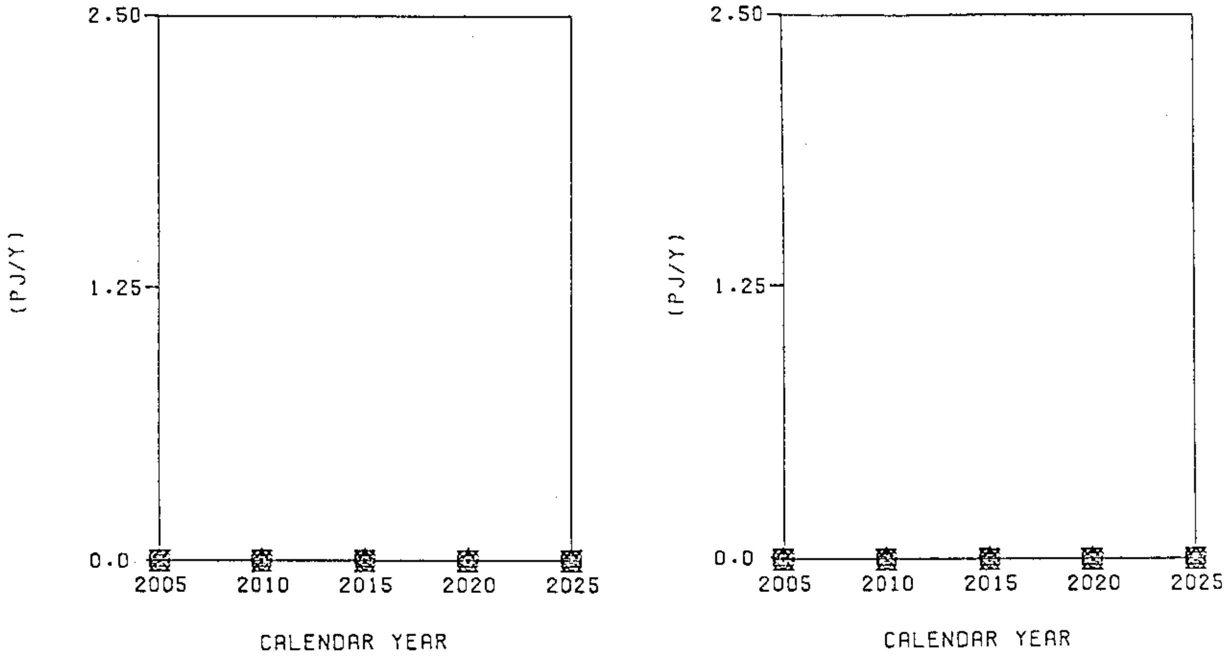
Thermochem. Heat Pipe

Fig. 12 Installed Capacity of IES Technologies (1)



Methane Steam Reforming

Thermochem. H_2 Production



High Temp. Electrolysis

Reducing Gas Production

Fig. 12 Installed Capacity of IES Technologies (2)

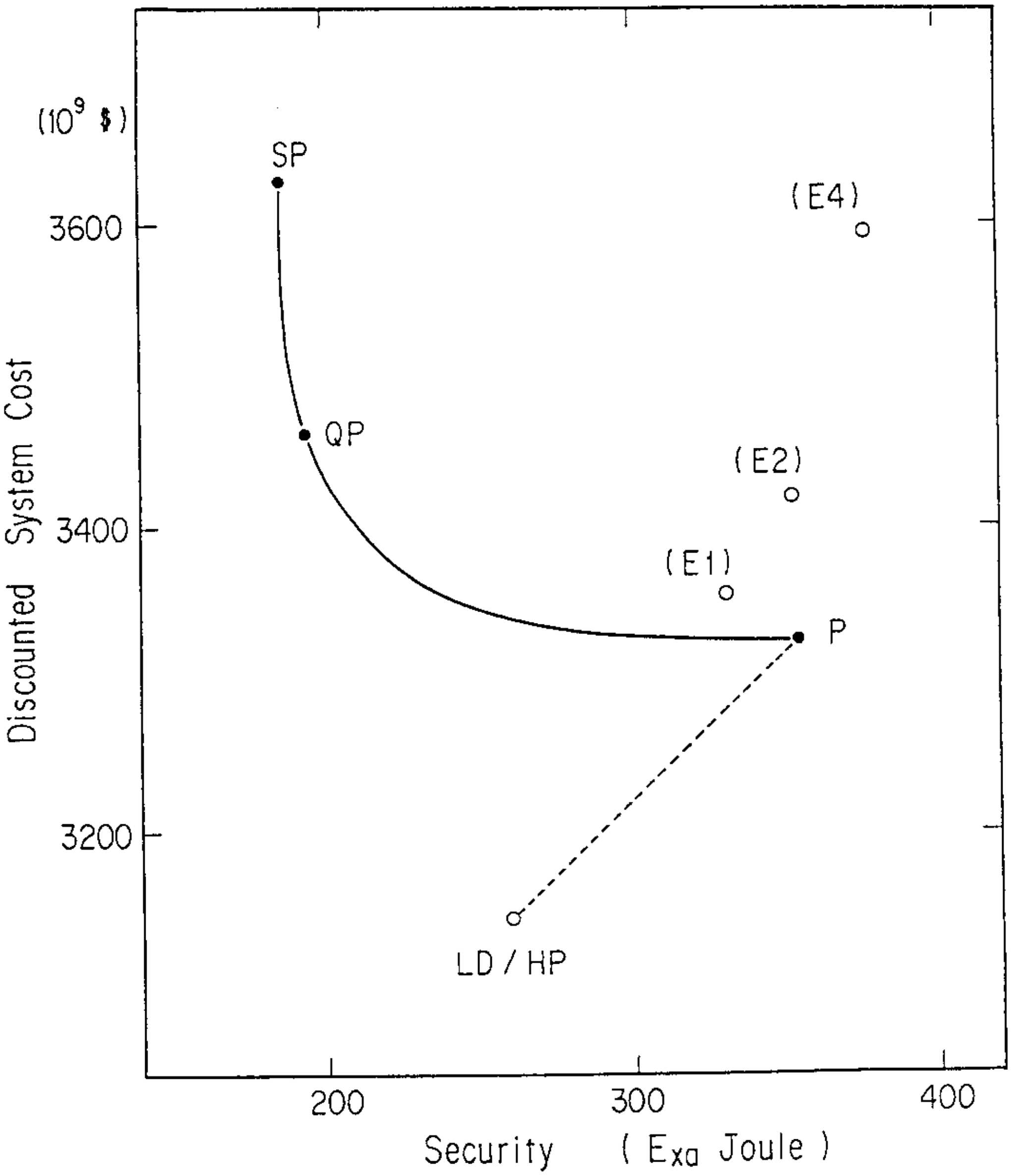


Fig. 13 Cost-Security Tradeoff in Reference Scenario

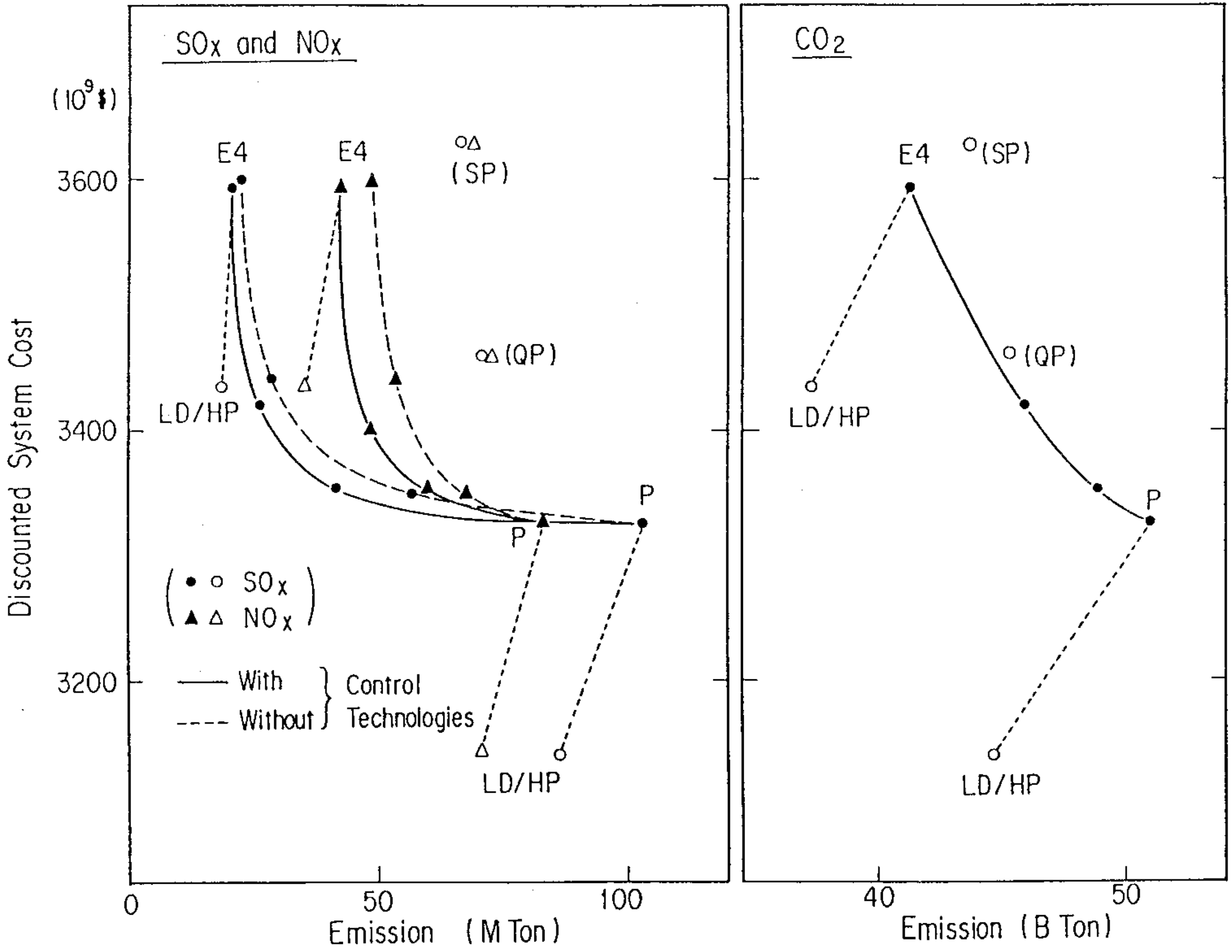
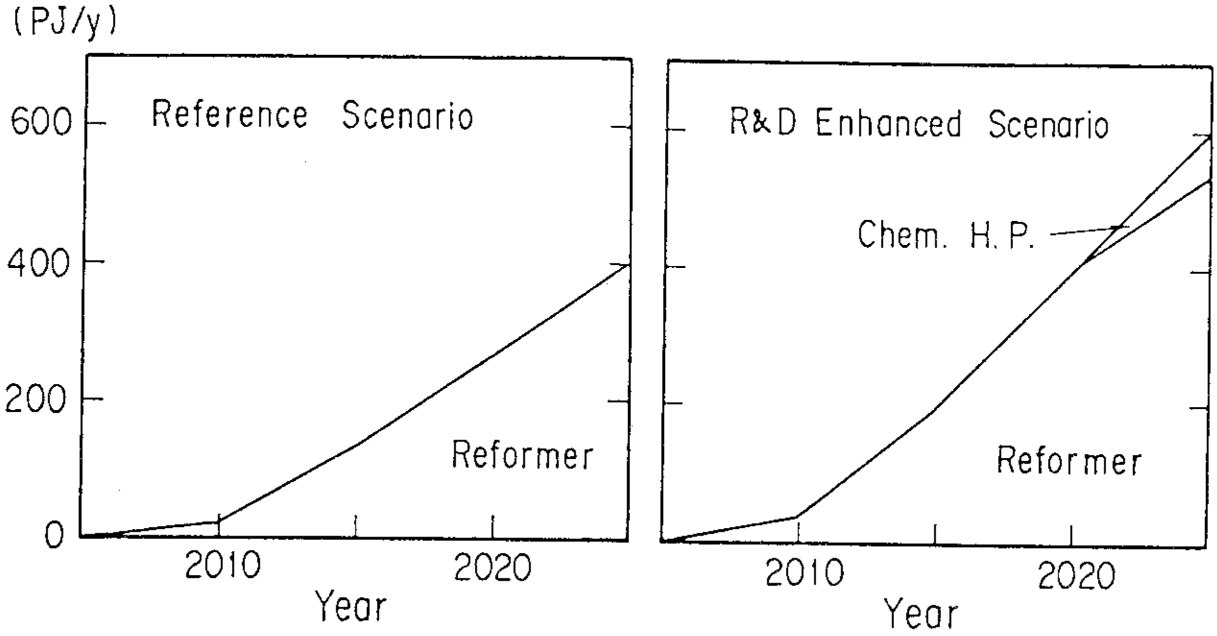
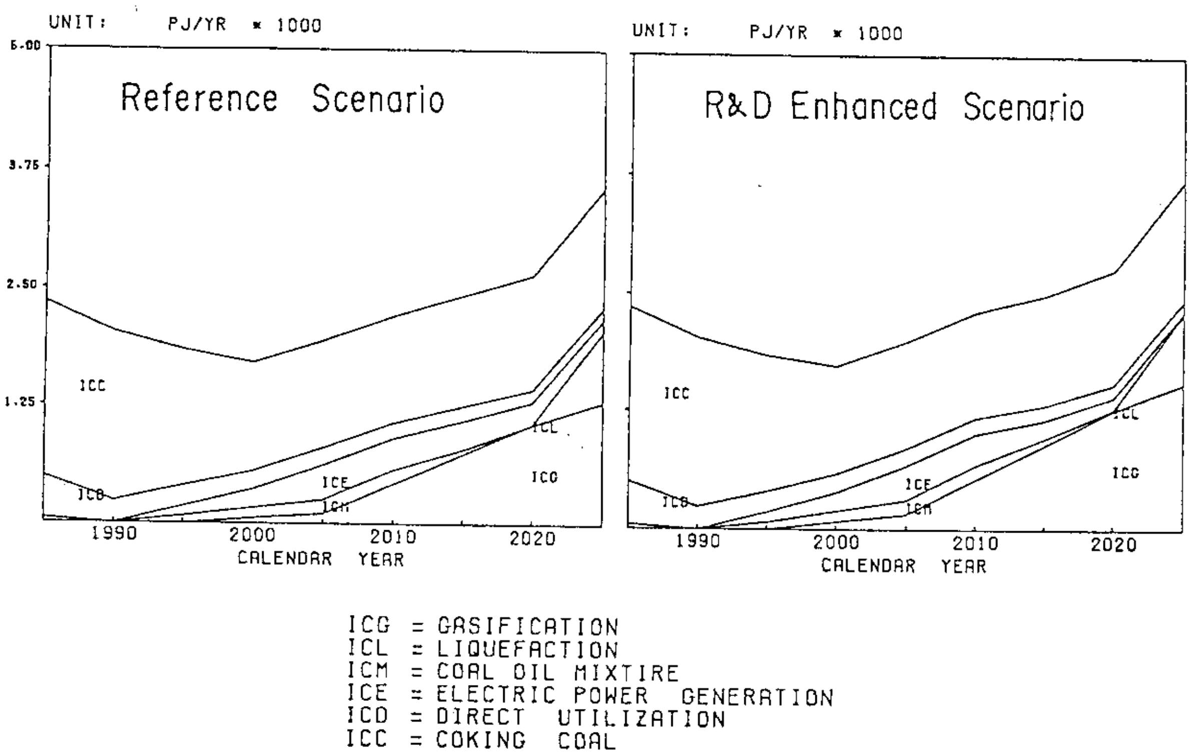


Fig. 14 Cost-Emission Tradeoff in Reference Scenario

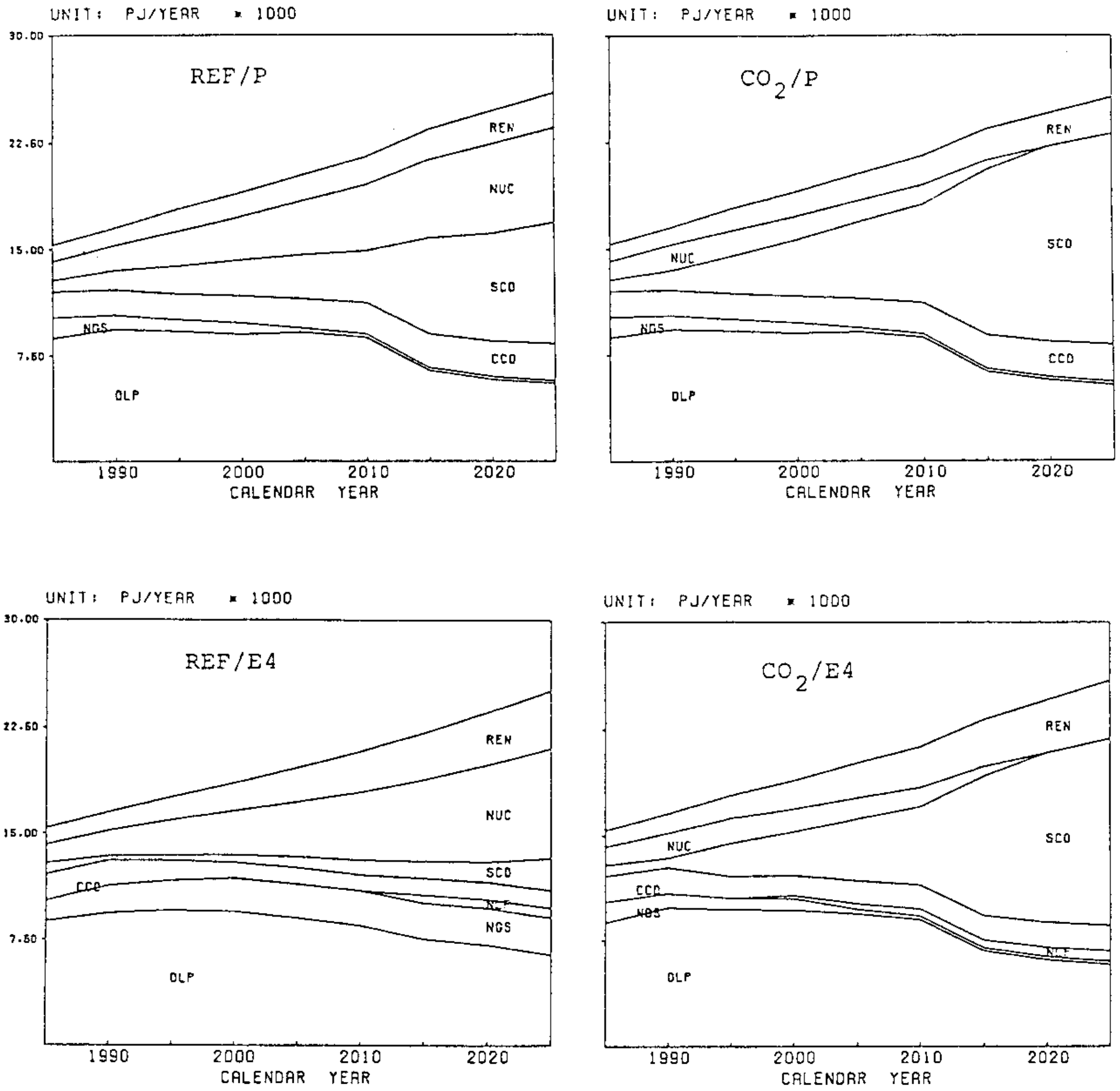


(a) Utilization of High Temperature Nuclear Heat



(b) Utilization of Coal

Fig. 15 Comparison of Reference Scenario and R&D Enhanced Scenario



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. 16(a) Comparison of Reference Scenario (REF) and CO$_2$ Shock Scenario (CO$_2$) – Primary Energy Supply

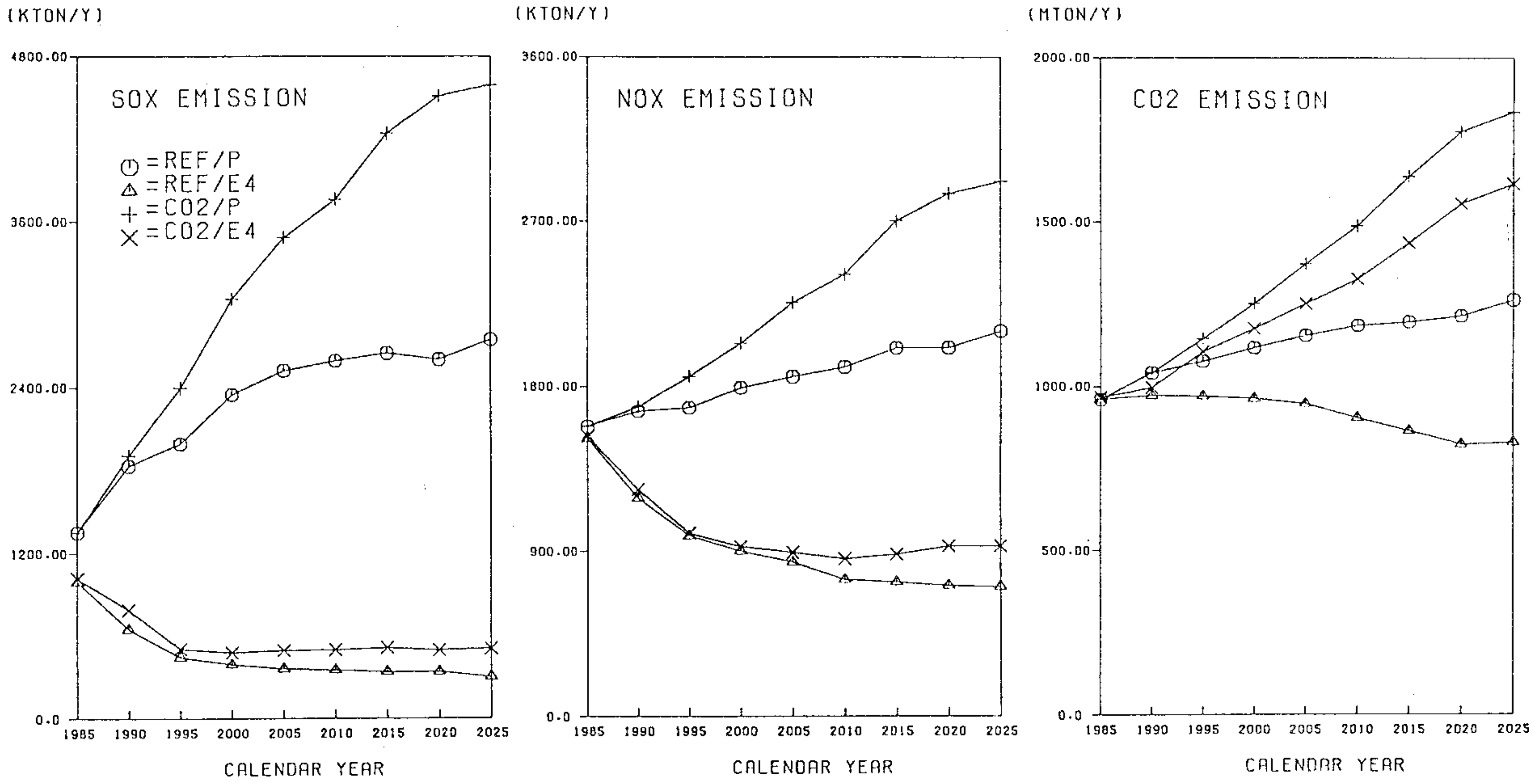


Fig. 16(b) Compariosn of Reference Scenario (REF) and CO_2 Shock Scenario (CO_2) – Environmental Emissions

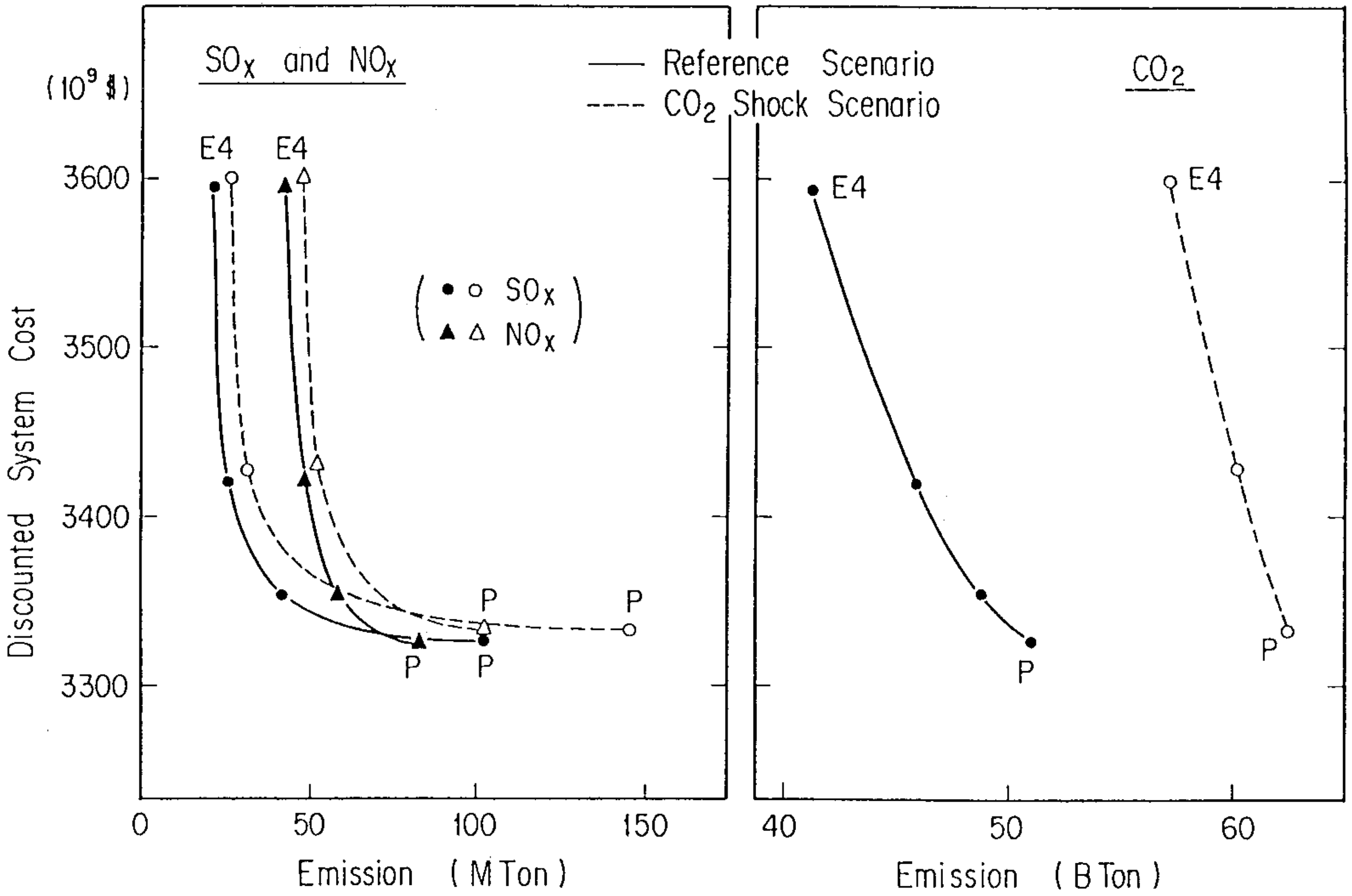
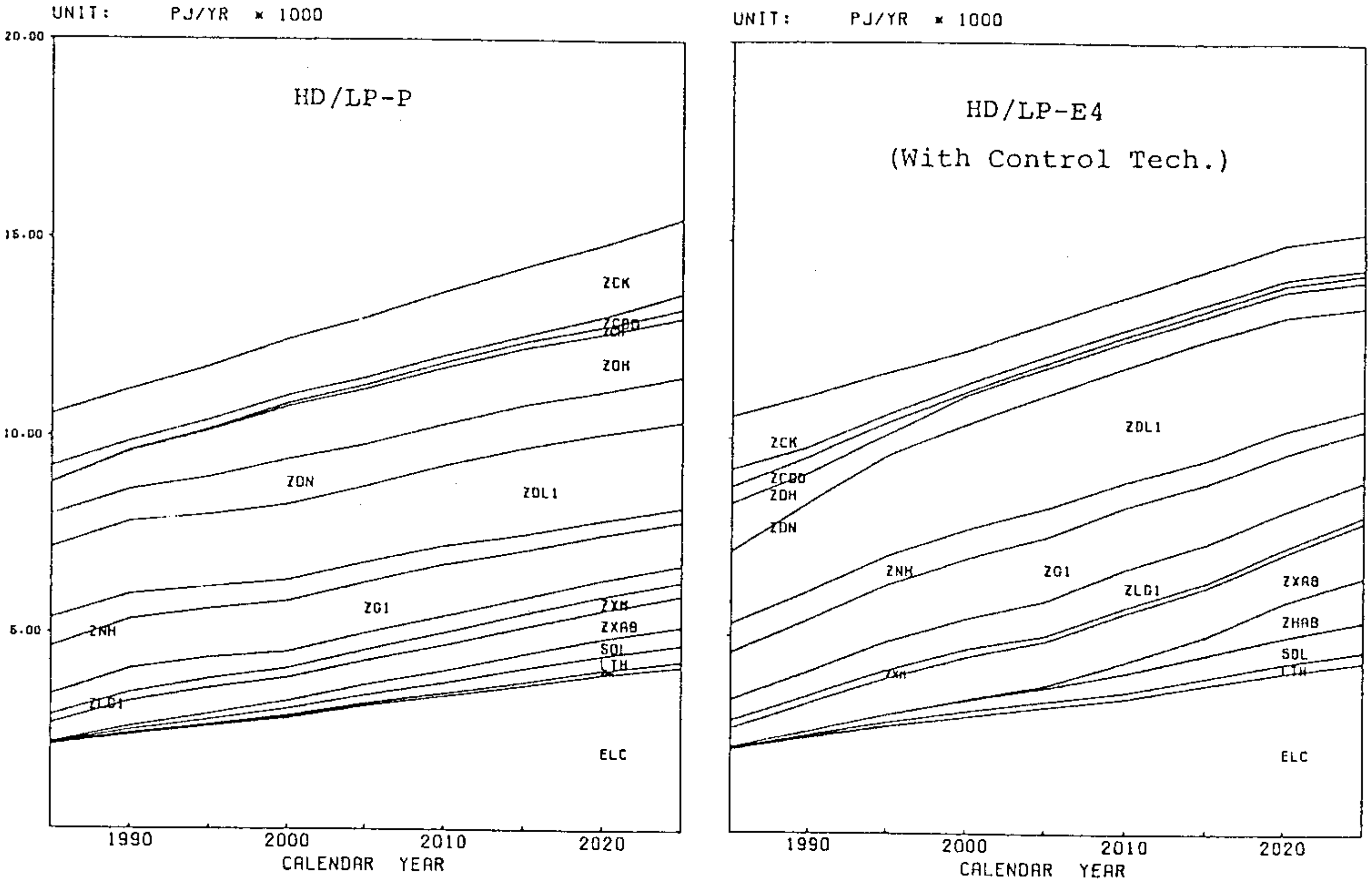


Fig. 17 Comparison of P-E Tradeoff Curve between Reference Scenario and CO_2 Shock Scenario



ELC = ELECTRICITY
ZPH = MED. TEMP. PROCESS HEAT
LTH = LOW TEMPERATURE HEAT
SOL = SOLAR
NSP = PROPULSION HEAT FOR NUCLEAR SHIP
ZHAB = HYDROGEN
ZXAB = TOWN GAS
ZXM = INDUSTRY GAS
ZLG1 = LIQUID PETROLEUM GAS

ZG1 = GASOLINE
ZNH = NAPHTHA
ZDL1 = LIGHT FUEL OIL (JET FUEL, KEROSENE, DIESEL)
ZDN = HEAVY FUEL OIL (LOW SULFUR)
ZDH = HEAVY FUEL OIL (HIGH SULFUR)
ZML = METHANOL
ZCDO = SOLID FUELS
ZCK = COKE

Fig. 18 Fuel Mix of Final Energy Consumption in Reference Scenario

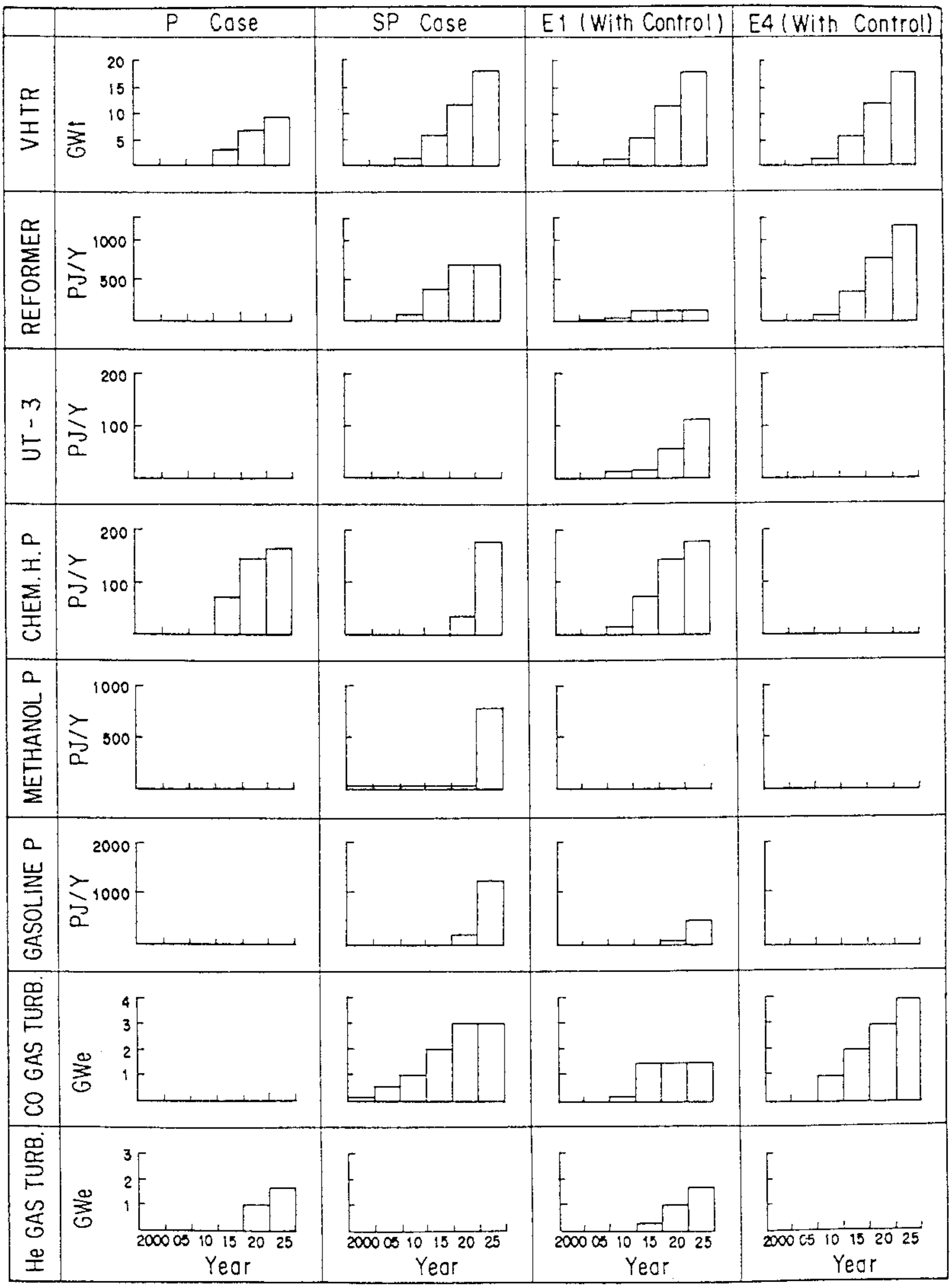


Fig. 19 Installed Capacities of IES Technologies
(Scenario: High Demand/Low Price)

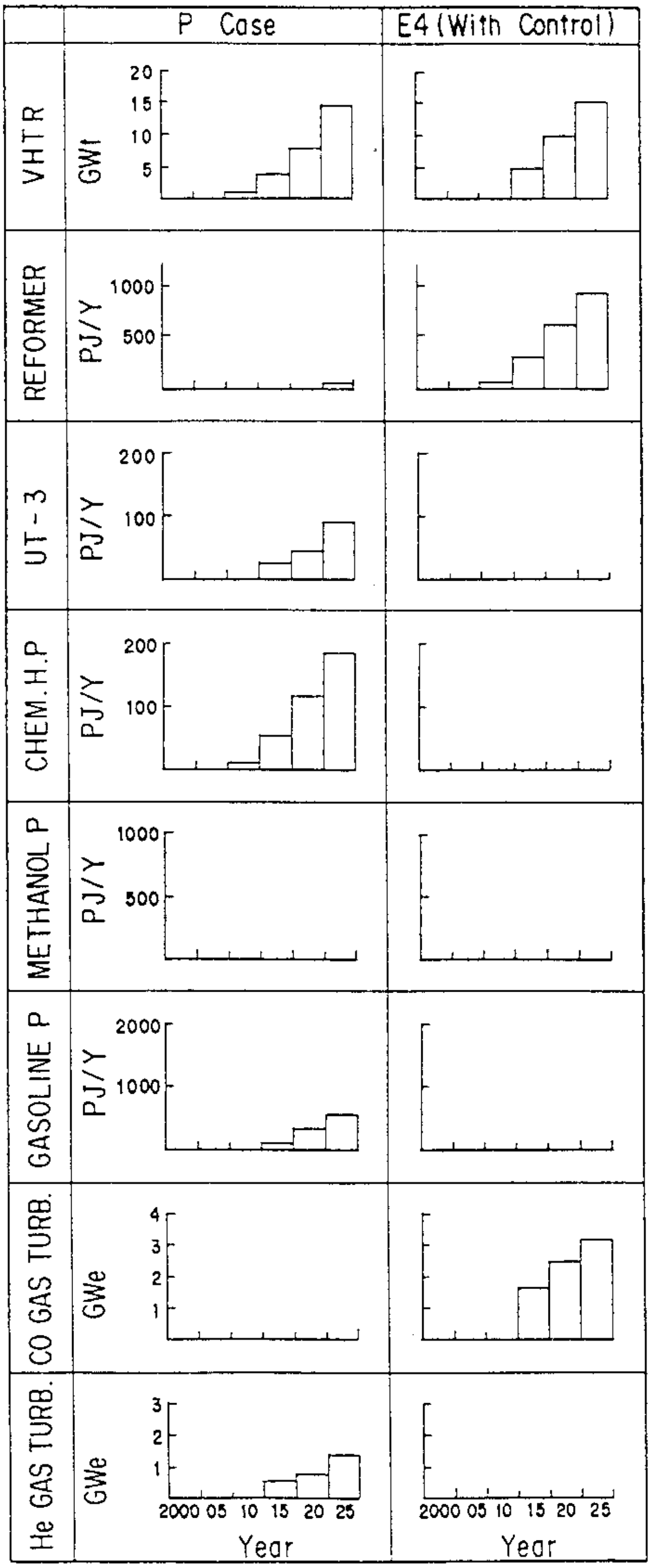


Fig. 20 Installed Capacities of IES Technologies
(Scenario: Low Demand/High Price)

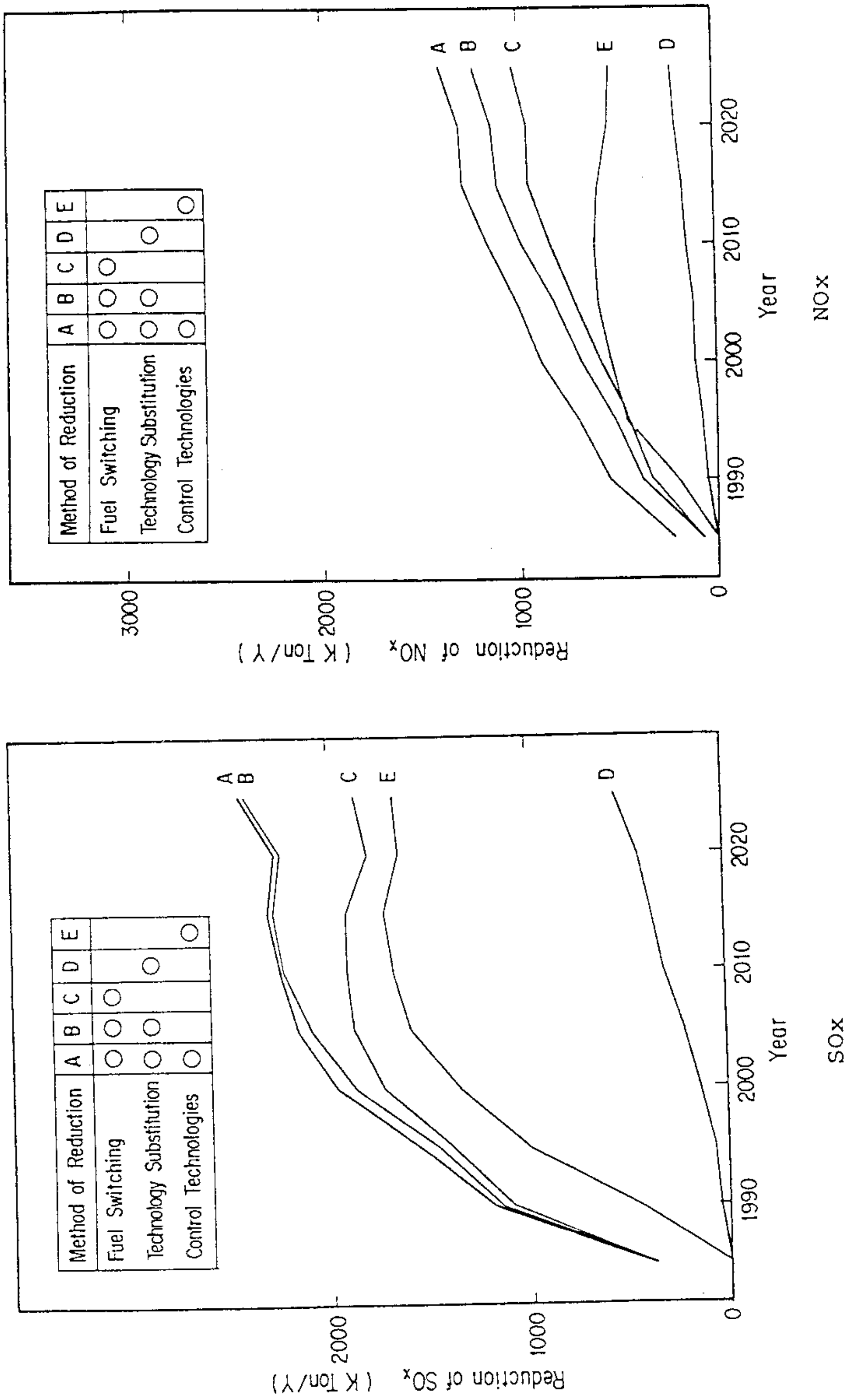
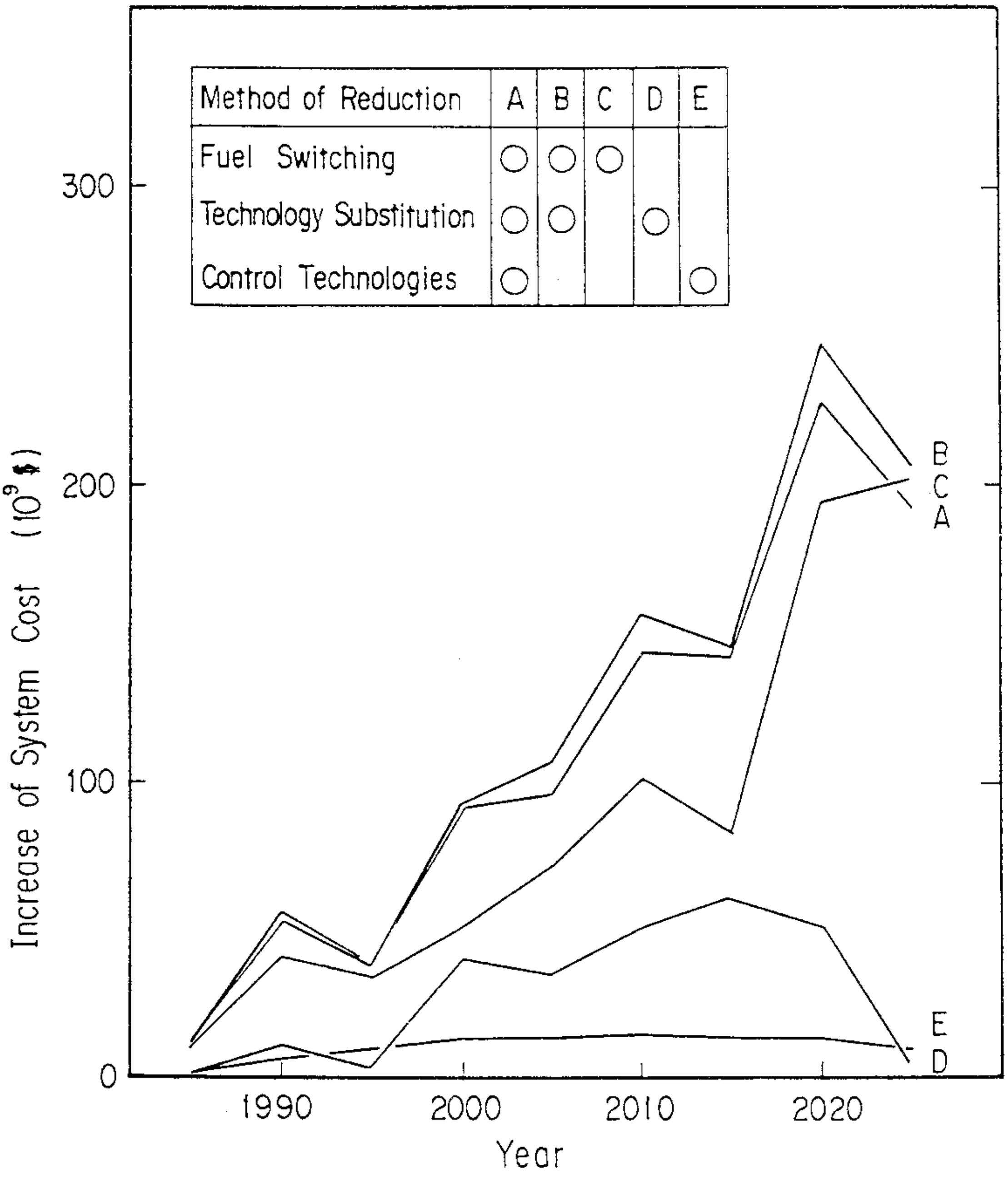


Fig. 21 Reduction of (SOx and NOx) Emission by Methods of Reduction



Method of Reduction	A	B	C	D	E
Fuel Switching	○	○	○		
Technology Substitution	○	○		○	
Control Technologies	○				○

Fig. 22 Increase of System Cost by Methods of Emission Reduction

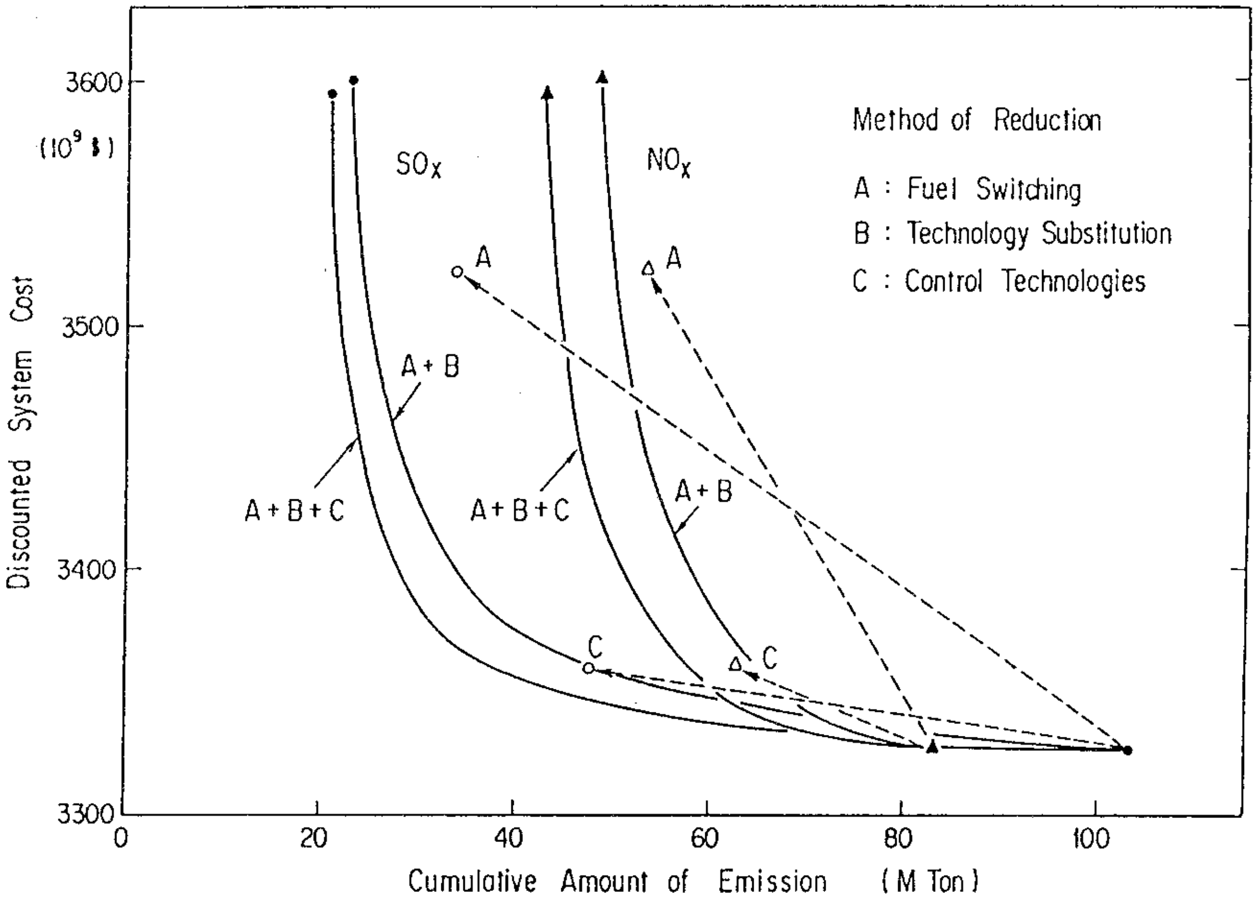


Fig. 23 Cost-Emission Tradeotfs by Methods of Emission Reduction