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AN ANALYSIS OF ENERGY STRATEGIES FOR CO_2 EMISSION REDUCTION IN CHINA

—CASE STUDIES BY MARKAL MODEL—

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An Analysis of Energy Strategies for CO_2 Emission Reduction in CHINA
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The China's energy system has been analyzed by using the MARKAL model in this study and the time period is from the year 1990 to 2050. The MARKAL model is applied here to evaluate the cost effective energy strategies for CO_2 emission reduction in China.

Firstly the Reference Energy System (RES) of China and its database were established, and the useful energy demand was projected on the basis of China's economic target and demographic forecasting. Four scenarios, BASE1-BASE4 were defined with different assumptions of crude oil and natural uranium availability.

Analytical results show that without CO_2 emission constrains coal consumption will continue to hold a dominant position in primary energy supply, and CO_2 emissions in 2050 will be 9.55 $BtCO_2$ and 10.28 $BtCO_2$ with different natural uranium availability.

Under the Co_2 emission constraints, nuclear and renewable energy will play important roles in CO_2 emission reduction, and feasible maximum CO_2 emission reduction estimated by this study is 3.16 $BtCO_2$ in 2050. The cumulative CO_2 emission from 1990 to 2050 will be 418.25 $BtCO_2$ and 429.16 $BtCO_2$ with different natural uranium availability. Total feasibile maximum CO_2 emission reduction from 1990 to 2050 is 95.97 $BtCO_2$.

Keywords: China, CO_2 Emission, CO_2 Reduction, Energy, Energy Strategies, Energy System, MARKAL

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中国における二酸化炭素排出抑制に対するエネルギー戦略解析
－MARKALモデルによるケーススターデー－

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（1994年11月28日受理）

本研究は中国のエネルギーシステムをMARKALモデルで分析した研究であり、対象期間を西暦1990年から2050年までとし、中国における二酸化炭素排出抑制の為の費用的に最も効果のあるエネルギー戦略を評価している。

はじめに中国の基準エネルギーシステムとそのデータベースが設定され、中国の長期人口予測、経済目標に則って有効エネルギー需要が作られた。そのうえで、石油と天然ウランの入手量に対してそれぞれ異なる前提をおきながら四種のシナリオBASE1-BASE4が導入された。

分析結果によれば、二酸化炭素排出抑制の制約がなければ石炭が一次エネルギー供給の主役を続け、二酸化炭素の排出量は天然ウランの入手次第で2050年に9.55$BtCO_2$から10.28$BtCO_2$にもなる。二酸化炭素の排出制約の下では原子力と自然エネルギー利用が重要な役割を果たし、二酸化炭素排出削減量は2050年に最大3.16$BtCO_2$可能である。1990年から2050年までの二酸化炭素の積算排出量は天然ウランの入手量にもよるが418.25$BtCO_2$から429.16$BtCO_2$になった。また、同期間における二酸化炭素排出削減の積算量の最大可能量は95.97$BtCO_2$であった。

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1. INTRODUCTION

1.1 Overview

Within the past several years, the global climate change issue has emerged from an esoteric field of research pursued by a few atmospheric scientists to the stage center of the international arena. A great deal of the attention has been paid to the so called Greenhouse effect by most of the governments and international organizations in the world. Since June 1988, the Conference on The Changing Atmosphere in Toronto, the topic has been virtually being a dominant theme of discussions of a number of international conferences and meetings at every corner of the world. Now the global warming has became an international political issue since the signatories to the Climate Change Convention of the UN Conference of Environment and Development held in Rio de Janeiro, Brazil.

The increase in atmospheric CO_2, which results primarily from combustion of fossil fuels is an important cause of the global warming. According to the assessment of the Working Group I of IPCC, the estimated contribution of CO_2 to the total radiative effect from 1980 to 1990 is of the order of 55%. The major share(some 75%) of man-made CO_2 emissions is caused by energy-related activities. If the assessment by the Working Group I of IPCC hold, then the energy policies will be a major factor in strategies designed to deal with the challenges of the global climate change.

China is the largest populated country in the world. The rapid historical growth of energy consumption in China, combined with the high proportion of coal use in the energy utilization, has made China one of the major contributors to the global release of greenhouse gases. In 1990, it consumed about 987 Mtce of primary commercial energy, which ranked third in the world (Fig. 1.1). According to the estimation of The Carbon Dioxide Information Analysis Center, ORNL, China emitted 623 million tons of carbon from fossil fuel combustion in 1989, that accounted for 10.8% of the global value (Table 1.1). As China has a large population, the energy consumption *per capita* in China is

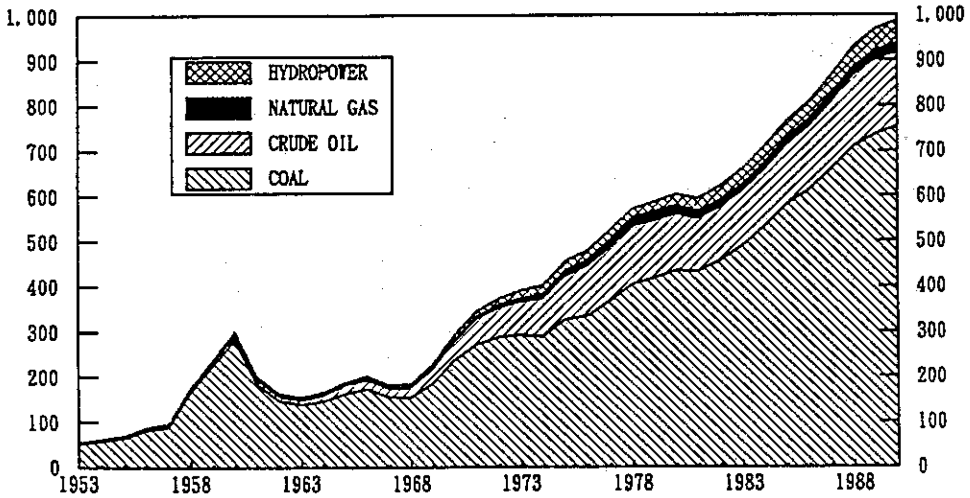

Fig. 1.1 China: Total Primary Energy Consumption and its Composition(Unit: Mtce)[1]

very low, less than one-half of the average level of the world, and the emission ***per capita*** also is very low.

Table 1.1 CO_2 Emission from Energy Use in 1989[2]

CO_2 Sources	Solid	Liquid	Gas	Total	Share	Per Capita
	(MtC)	(MtC)	(MtC)	(MtC)		(TC)
US	498	567	252	1317	22.9%	5.32
USSR	363	338	308	1008	17.5%	3.51
China	536	80	7	623	10.8%	0.56
Japan	83	165	25	273	4.7%	2.22
Indian	126	39	4	169	2.9%	0.20
World	2392	2419	946	5757	100.%	1.11

In the near future, China will continue to industrialize its economy and to make people's life relatively rich. The energy consumption will also be increased in order to power its economic and social development. If CO_2 emission becomes an important constraint, combined with the energy resources and technology development factors, to the energy system, it is necessary to make systems analyses on the total China's energy system in order to understand their implications and to investigate the response strategies for implementing efficient measures to reduce CO_2 emission.

1.2 Purpose of This Study

Some researches on China's energy development and on related CO_2 emission are available at home and abroad[3,4,5,6,7,8,9,28] since China will play an important role in the global CO_2 emission. Usually these researches paid more emphases on China's energy demand forecasting, but made few discussion about the countermeasures for CO_2 emission reduction. Xi Xiaolin[10] used firstly the MARKAL model to assess China's energy development and CO_2 emission reduction with more technological detail in BNL. But there are only 84 kinds of resources and technologies in his database, and the time span covers only 35 years from 1985 to 2020 because PC-MARKAL he used deals with at most nine 5-year periods.

This study is intended to analyze the strategies of CO_2 emission reduction in China in more technological detail from the year of 1990 to 2050 by using the MARKAL model of JAERI's version. That is to say by using analytical methods based on the MARKAL model which has been developed within the IEA's Energy Technology System Analysis Program(ETSAP), the assessment has been made to calculate how China can best reduce carbon dioxide emission from its energy system and how Chinese energy system could best respond to possible future restrictions on carbon dioxide emission.

The 60-year time horizon is chosen because for this time span China will basically realize the modernization according to Chinese government's economic target. The macro-economic structure will change greatly. These depend on energy and will also influence the structure of energy system. We can not hope that the high proportion of coal use in China's energy system will be changed greatly within a short-term if we take into account of social, economic and energy resources constraints. It is only meaningful to evaluate China's energy system in a long-term from view points of possible change of fuels and technologies.

As a bottom-up model, the MARKAL can provide a wealth of detail results on the choice of technologies measures with their implications on the use of fuels, the needed resources, and the emissions of CO_2. But it should be noted that MARKAL is a normative model which is used to design future energy systems in a parametric way, that is, by examining a range of possibilities. It is not a simulation model to predict the future[16].

2 ANALYTICAL METHODS

2.1 The MARKAL Model

MARKAL(MARKet ALlocation) is a generalized bottom-up dynamic LP optimization model of energy system which has developed since 1976 and 1983 as a multinational collaborative effort within the framework of the International Energy Agency(IEA). It can be considered as a Model Construction Kit for formulating various kinds of detailed national or sub-national energy systems which is built on the concept of a Reference Energy System(RES). MARKAL allows a detailed description of existing and alternative energy technologies and of existing and alternative paths of energy carriers from their source – through different conversion technologies – until the point of final use.

MARKAL essentially creates a market in which energy resources, supply technologies and end-use technologies compete to meet these energy service demands. Upper bounds can be set on the maximum extent of market penetration and rate of growth of market penetration for each technology, but within those constraints, MARKAL determines the level of market penetration of each technology in the results. MARKAL is an inherently flexible model which is able to address a wide range of energy and environmental issues. It has been adapted for use in many countries to model national, provincial, and local energy systems, especially used as a common analytical tool by IEA's Energy Technology System Analysis Program(ETSAP). Coupled with the MARKAL Users Support System on a microcomputer, MARKAL is a responsive, user-friendly modelling system for energy-environmental analysis, planning, and policy making[11,12,13,14,15].

MARKAL is solved by means of dynamic linear programming. In many applications, the end use demands are fixed, and the objective function is the total discounted cost of the energy system over the entire time horizon, which implies cost-optimal energy strategies. The objective function may also consists of the weighed sum of this cost and environmental emissions, which could be interpreted as a Emission Tax. Another way to treat emission reductions is modelling emission reductions by introducing constraints that sets limits on the maximum amount of emissions. Applied to greenhouse problem, these aimed at such a solution: how much will it cost to reduce greenhouse gases emissions.

In brief, the advantages of the MARKAL model are as follows:

1) Technological and cost data are included on the level of the individual type of technology;
2) The time horizon is long enough to change the technological mix;
3) Prices are calculated from technological as well as cost data;
4) Responses of supply and demand are analyzed at the same time;
5) Supply technologies can be compared directly with those for end-use;
6) A wide range of energy systems can be modeled to a chosen level of detail;
7) Tradeoff relationship between the use of energy resources and environmental emissions and/or the system cost can be searched.

2.2 Analytical Scenarios and Cases

2.2.1 Scenarios

Several scenarios are defined in order to address important issues in CO_2 emissions associated with China's energy system utilizing social and economic scenario indices. The current structure of energy consumption in China is determined by the structure of her recoverable resources. The fuels switch from coal to oil and gas will depended on their availability from new discovered oil fields or imported from foreign country. This study regards this as an important factor in the scenario's construction. In order to investigate the possible range of CO_2 emission reduction, scenarios with assumption of high and low crude oil supply are created. In the scenario with assumption of high oil supply, both new discovered oil resources and imported oil are supposed to be available in the future. On the contrary, the scenario with assumption of low oil supply assumes that these energy resources are unavailable in the future for China.

The technology substitution by introducing nuclear and renewable energy technologies seems to be the irreplaceable choices in CO_2 emission reduction for China. Referring to other researches about the comparative economics of nuclear power plants vs. coal power plants, this study assumed that nuclear power generation will be more economical by a small margin than coal power generation in many parts of China[10]. But there are also many factors which will affect China's nuclear energy development. For example, the natural uranium resource and the initial investment cost. For the sake of clearly analyzing the potential role of nuclear energy in CO_2 emission reduction, scenarios with imported natural uranium and without imported natural uranium were defined. And this study supposed that the LMFBR, LWR co-generation and VHTR technologies will be available in the future. For all scenarios no constraints to the domestic coal resources is postulated.

In brief, all the scenarios in this study are summarized in the following table:

Table 2.1 Description of Scenarios

SCENARIO	DESCRIPTION
BASE1	Both imported oil and natural uranium available
BASE2	Imported oil available, no imported natural uranium
BASE3	No imported oil, imported natural uranium available
BASE4	No imported oil, no imported natural uranium

2.2.2 Cases

For each scenario, firstly a baseline, or reference case (P case) when discounted system cost is optimized as an objective function without external constraints on CO_2 emission is run. This constitutes the starting point for further assessments. There will be several baseline projections in this report according to the different energy resources constraints of the assumed scenarios.

After P case analysis, a Carbon Tax case (E case) and a Minimum CO_2 Emission case (M case) have been calculated. For the E case, a surcharge is imposed on CO_2 emissions which increases from 20 US\$/ton(CO_2) in 1990 to 410 US\$/ton(CO_2) in 2050. The surcharge is discounted back to the reference year and the objective function is the sum of the discounted system cost and the surcharge on CO_2 emission. For the M case, just the cumulative CO_2 emission is used as the objective function.

Tradeoff relationship between discounted system cost and CO_2 emission has been analyzed in this study. Six cases(P1, P2, P3, P4, P5, P6) with different surcharges on CO_2 are calculated in the tradeoff analysis.

2.3 Reference Energy System

2.3.1 System Structure

China's energy system from 1990 to 2050 is modelled as a Reference Energy System(RES) according to the MARKAL model frame (Fig. 2.1, 2.2). RES is a total energy system which covers all the processes from primary energy sectors to final energy sectors through conversion, storage, transport and distribution of secondary energy carriers. RES is expressed by energy carriers and energy technologies, and is characterized by the technological behavior.

Technology element of the set (TCH) is classified into the following three groups:

1) Conversion technologies (CON) such as production, storage and supply of electricity and low temperature heat;
2) Process technologies (PRC) such as production, storage and transport of energy carriers of oil products, coal products and hydrogen etc.;
3) Demand technologies (DMD) utilized in the final demand sectors.

Energy carriers are divided into:

1) Electricity (ELC);
2) Low Temperature Heat (LTH);
3) Other energy carriers (ENC).

In this study, the China's RES contains 77 kinds of energy carriers and 214 kinds of energy technologies (27 kinds of conversion technologies, 55 kinds of process technologies and 132 kinds of demand technologies), and 30 kinds of demand sectors. The distinctive features of China's RES are explained as follows:

1)**Sectoral Demand and End-use Technologies** The demand for energy is disaggregated into five major sectors: agriculture, industry, service, residential and transportation. In these sectors specific useful energy demands are exogenously given for each time period over of the time horizon considered. The sectors are subdivided into different end-uses, such as motor power, space heating, and cement production, etc.. The useful energy demands are exogenously outside the model. End-use technologies connect the specific energy demands with the secondary energy carriers (presented in the most left column) which are presented by circles in Fig. 2.2. For some technologies such as iron and steel making , casting and milling in the iron and steel production, more than one energy carriers are used which are presented by the asterisks in the circles.

2)**Conversion of Primary Energy** Fig. 2.1 is a part of the China's RES which converts the primary energy into the secondary energy carriers. In this part MARKAL can again choose between different conversion and process options to satisfy the need for secondary energy carriers.

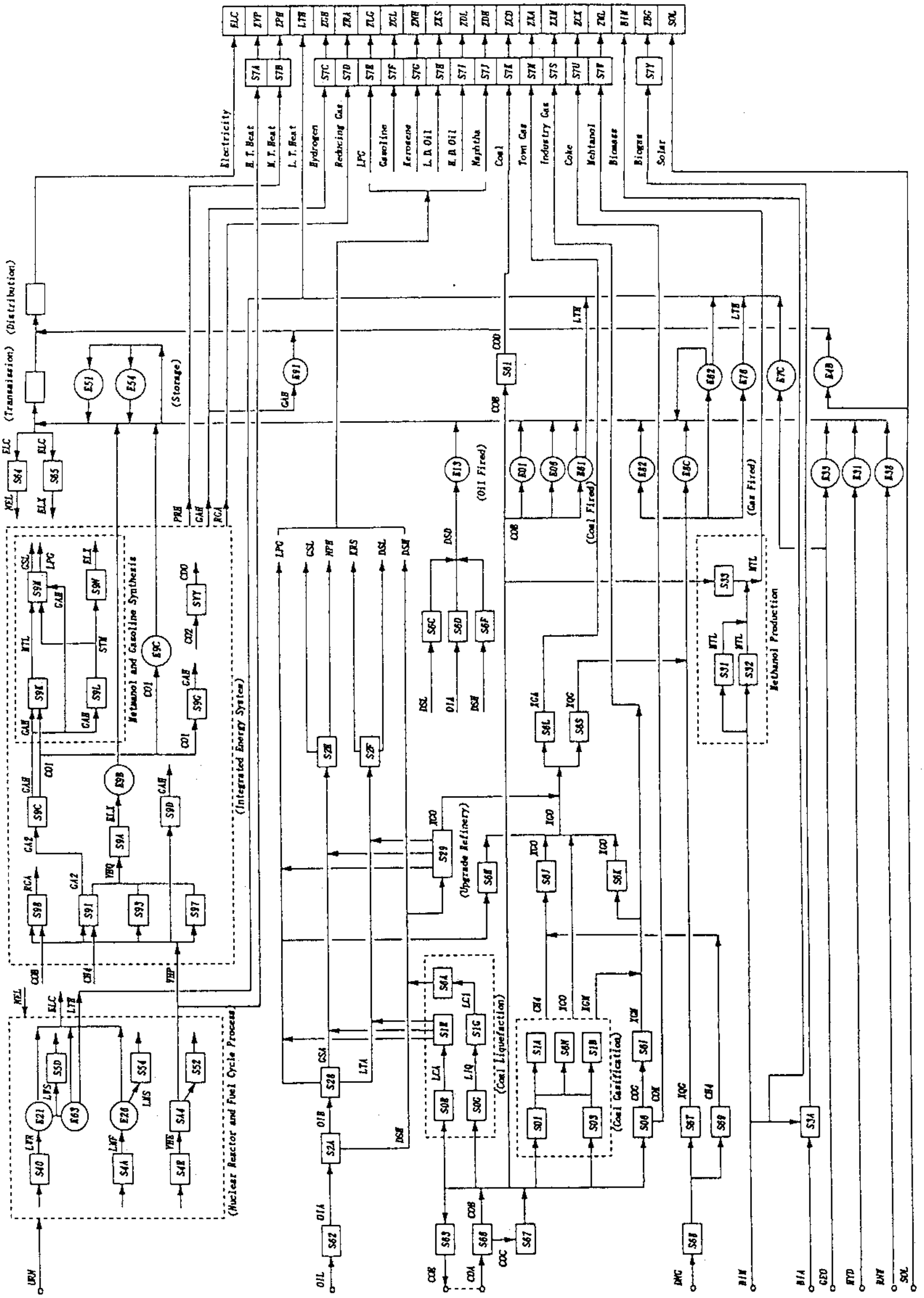

Fig. 2.1 China: Reference Energy System(1/2)

SECTOR		AGRICULTURE & INDUSTRY																SERVICE & RESIDENTIAL												TRANSPORTATION									
		AGRI.		INDUSTRY														SERVICE				RESIDENTIAL								PASSENGER					FREIGHT				
TECH.				COMMON			CHEMICAL				IRON & STEEL			CEMENT		PAPER						URBAN					RURAL												
FUEL		Agri. Motor	Agri. Heating	Motor	Boiler	Furnace	Motor	Boiler	Furnace	Material	Making	Casting	Milling	Motor	Kiln	Motor	Boiler	Light & Appli.	Space Heating	Wate Heating	Air Condition	Light & Appli.	Space Heating	Wate Heating	Cooking	Air Condition	Light & Appli.	Space Heating	Cooking	Railway	Automobile	Bus	Ship	Air	Railway	Truck	Ship	Air	Pipeline
		I1	I2	I3	I4	I5	IK	IL	IM	IN	IA	IB	IC	IX	IY	IP	IR	R1	R2	R3	R4	RA	RB	RC	RD	RE	RF	RG	RH	T1	T1	T1	T1	T1	TA	TA	TA	TA	TA
Electricity	ELC	①		①		①	①		①		⊛	⊛	⊛	①		①		①	①	①	①	①	①	①	①	①	①			①	Ⓔ	⑨			①	⑤			⊛
H. T. Heat	ZVP										⊛																												
M. T. Heat	ZPH				⑤																																		
L. T. Heat	LTH				⑥														⑥	⑥			⑥	⑥															
Hydrogen	ZGH					Ⓐ				Ⓐ																					④	Ⓑ		Ⓛ		Ⓑ		Ⓛ	
Reducing Gas	ZRA										⊛																												
LPG	ZLG				Ⓗ	Ⓗ		Ⓗ	Ⓗ			⊛								Ⓗ				Ⓗ	③				③										
Gasoline	ZGL	②																													⑥	Ⓙ				⑦			
Kerosene	ZKS				Ⓚ	Ⓚ		Ⓚ					⊛						Ⓚ								②							Ⓜ				Ⓚ	
L. D. Oil	ZDL	③		Ⓛ																										②	⑦	Ⓚ	Ⓠ		②	⑨	Ⓠ		
H. D. Oil	ZDH				Ⓠ	Ⓠ		Ⓠ		Ⓟ	⊛		⊛		Ⓠ		Ⓠ		Ⓠ																				⊛
Naphtha	ZNH									Ⓘ																													
Industry Gas	ZXM				Ⓔ	Ⓔ		Ⓔ	Ⓔ				⊛																										
Town Gas	ZXA				Ⓕ	Ⓕ		Ⓕ	Ⓕ	Ⓗ	⊛	⊛	⊛						Ⓕ	Ⓕ	Ⓕ			Ⓕ	④				④		⑤	Ⓖ				Ⓒ			⊛
Coal	ZCD		①		Ⓤ	Ⓤ		Ⓤ	Ⓤ	Ⓤ	⊛				Ⓤ		Ⓤ		Ⓤ	Ⓤ			Ⓤ	Ⓤ	②			①	①	③					③				
Coke	ZCK					Ⓥ			Ⓥ	Ⓥ	⊛	⊛																											
Methanol	ZML				Ⓡ																										⑧	Ⓐ				Ⓙ			
Biogas	ZBM																											②	②										
Biogas	ZBG																												Ⓑ										
SOLAR	SOL		②		⑦														⑧	⑧			⑧	⑧				⑧	Ⓐ										

Fig. 2.2 China: Reference Energy System(2/2)

As for the electrical power generation technologies, fossil fuel, nuclear energy and renewable energy such as hydraulic power, co-generations and electrical power storages such as pumped storage power generations and fuel cells are considered. The demands of low, intermediate and high temperature heat are distinguished from heat supply, and co-generation, solar energy, geothermal energy and other renewable energy such as wind energy are utilized.

Concerning process technologies, the RES includes production of various kinds of oil products such as LPG, gasoline, naphtha, kerosene, heavy oil etc., which are processed by oil distillation, refinery, lighting and cracking process. Town gas is produced by coal gasification or from other synthetic fuel production. Coal liquefication and methanol production from biomass and coal are also considered.

In order to investigate the possibility of symbiotic use of nuclear heat and fossil fuel through hydrogen, the concept of the Integrated Energy System(IES) is introduced in China's RES. The technologies in the IES includes the high temperature gas cooled reactor and methane steam reforming, water thermal splitting, high temperature electrolysis, reducing gas production for nuclear iron and steel making, and methanol synthesis etc..

3)**Energy Resources** The domestic primary energy carriers are within the borders of the MARKAL model, which are natural uranium, coal, crude oil, natural gas, hydropower, biomass, solar, geothermal and other renewable energy(e.g. wind and wave energy). As mentioned in the description of scenarios, import is also considered for crude oil and natural uranium.

In China's rural country, large amounts of biomass which includes mostly firewood and crop stalks are used by residential sector. This study simply assumes that 7323 PJ(about 250 Mtce) biomass has been used in 1990, and it will decrease to 2634 PJ(about 90 Mtce) in 2050.

2.3.2 Data Base

The richness of the MARKAL analysis depends on the technology and resources database. To build a model, the following data are required:

1) Energy forms to be represented in the model;
2) Kinds of technologies and their characteristics;
3) Available quantity of domestic primary resources;
4) Prices for imported and exported resources;
5) Useful energy demand for sectors;
6) Other constraints, such as emission limits.

The compilation of information on technology is the most important but tedious in establishing the MARKAL database since the database is composed mainly of technical coefficients describing the energy inputs and outputs of a very large set of technologies, their efficiencies, costs (investment and operation, fixed and variable), lifetime, dates of availability, emission, etc..

Constrained by the time available for the analysis and constrained by the China's data resources available for this analysis, the database of Japan's energy system compiled by Energy system Assessment Laboratory, JAERI and the technology databooks edited by IEA/ETSAP are used but for some technical data are directly used[18,19,21,22]. But the efficiency and cost data have been modified as possible as the data's availability.

For the reference year 1990, the energy supply and demand data are referred to the China's statistical figures. Since the categories of demand sectors in the RES are different from the China's statistical categories, adjustment has been made to the statistical data.

2.4 Approach to Useful Energy Demand Projection

MARKAL requires exogenously specified useful energy demands for each categories. Theoretically, and in the physical sense, **useful energy** represents energy in the form which is actually required by the consumer: heat for heating, light for lighting, mechanical power for movement, etc[23]. This implies in particular that the so-called final energy consumption of the various demand sectors is not exogenously specified, but is rather determined by the model as a result of competition among the demand technologies which satisfy the useful demands. The competition will usually result in the substitution among the fuels[16].

Useful energy here refers to the part of energy consumed effectively and is defined as the energy input to the demand technologies minus loss of energy during consumption. In order to analyze the potential of energy conservation technologically, the physical amounts of production are employed for crude steel, cement and paper instead of using useful energy directly for the associated sectors. For the transportation sector, person-kilometers(pkm) and ton-kilometers(tkm) are used for the same purpose.

In this study, a sectoral end-use analysis method is adopted to project the useful energy demand according to the sector's category of China's RES. The results of useful energy demand shown in section 2 are based on the improvement of energy intensity and many other parameters of economic and energy development.

Because the emphasis of this study is the strategies analysis of CO_2 emission reduction, and also because of the author's limited time in JAERI, information and results have been extensively used from these researches: **Energy Demand of China in 2050**[7], **Energy Development and CO_2 Emission in China**[10] and **Sectoral Energy Demand Analysis of China--the Application of MEDEE-S Model in China**[29].

3. PROJECTION OF USEFUL ENERGY DEMAND

3.1 Assumption of Demographic and Economic Development

In order to calculate demands for energy services, i.e. useful energy demands, scenarios for the long-term social-economic development of China has been constructed. These data are used as basic instrument for estimating useful energy demands which drive the MARKAL model as the exogenous parameters of the total energy system.

3.1.1 Demographic Data

China has the world's largest population with 1143 million people in 1990. There are several researches about the future population development of China to the year of 2050[6,9]. The population scenarios in these researches can be summarized in the following figure:

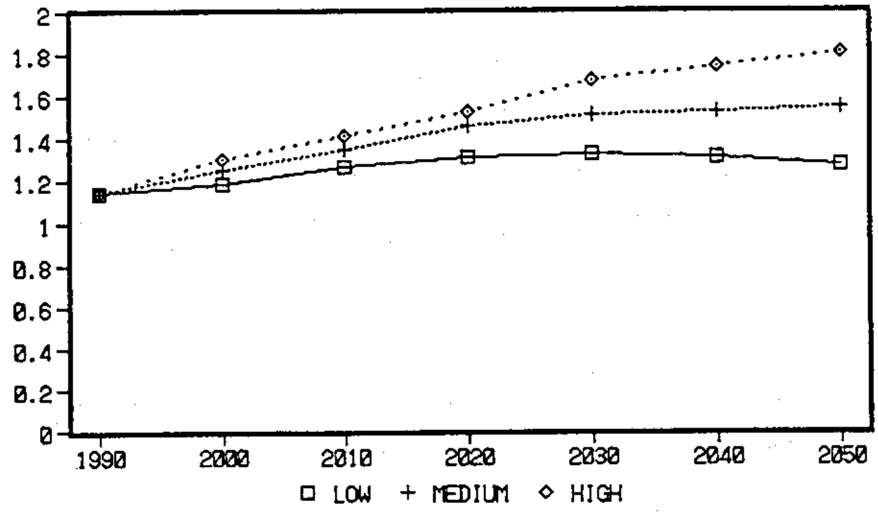

Fig. 3.1 Population Scenarios of China(Unit: Billion)

This study assumes that the future population development of China will follow the medium scenario in the Fig. 3.2, and the demographic data are 1250, 1340, 1410, 1450, 1480, 1500 Million in 2000, 2010, 2020, 2030, 2040, 2050 respectively. The population composition are assumed as Table 3.1.

3.1.2 Economic Data

1) **Growth rate of GNP *per capita*** The assumption of China's economic development based on the Chinese government's plans for its economy which can be principally divided into the following three stages with different targets:

The first one was to double her GNP ***per capita*** of 1980 and solve the problems of feeding and clothing her people. This target has been basically attained until the year of 1987.

The second one is to quadruple her GNP ***per capita*** of 1980 by the turn of this

Table 3.1 Population Composition of China(Unit: Million)

Year	1990	2000	2010	2020	2030	2040	2050
Total	1143	1250	1340	1410	1450	1480	1500
Urban	302	450	647	818	928	1006	1050
%	26.4	36	48	58	64	68	70
Rural	841	800	693	592	522	474	450
%	73.6	64	52	42	36	32	30

century and to lay a solid foundation for her economic soar in the next century.

The third one is that her GNP *per capita* should reach the level of the middle-developed countries by the middle of the next century and the nation would basically realize the modernization[5].

In the past decade, the nationwide economic reforms have made Chinese economic development keep a high growth rate compared with that of other countries. The targets mentioned above are not difficult to reach for China if this trend continues for several decades. This study makes the scenario for China's economic development as follows: the GNP *per capita* growth rate is consistent with the government's targets and the GNP *per capita* will double the value of 1990 in the year of 2050. This economic scenario can be seen as a low GNP *per capita* growth rate scenario for China.

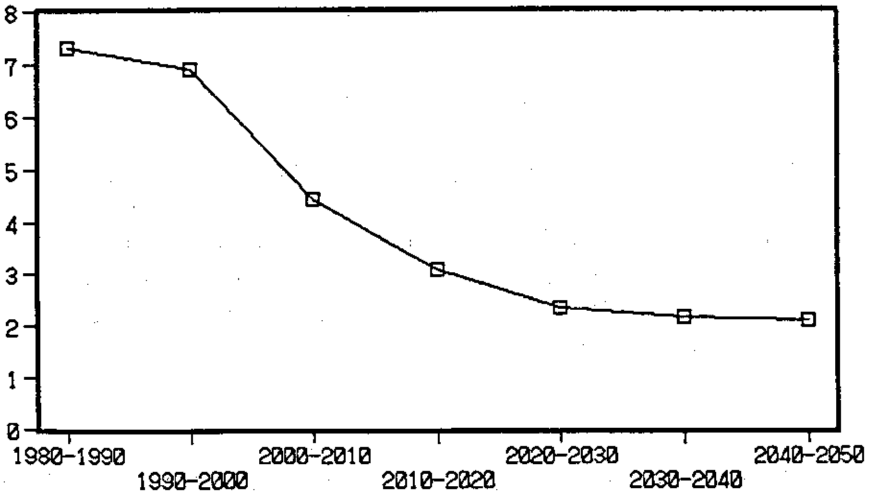

Fig. 3.2 GNP *per capita* Growth Rate of China

2) **GNP *per capita* and GNP** In 1980 and 1990 the GNP *per capita* in China was 304 and 616 US$ (Constant 1980 Price, Exchange Rate: 1.49 Chinese Yuan/US$) respectively[3]. With the assumed population and growth rate of GNP *per capita,* we can get the scenario value of GNP *per capita* and GNP in China to the year of 2050 (Table 3.2, Fig 3.3).

Table 3.2 GNP *per capita* and GNP Scenario of China (Unit: GNP *per capita* US$, GNP Billion Constant 1980 US$)

Year	1980	1990	2000	2010	2020	2030	2040	2050
GNP/p	304	616	1200	1850	2500	3150	3900	4800
G.R(%)		7.32	6.90	4.42	3.06	2.34	2.16	2.10
GNP	300	705	1500	2479	3525	4568	5772	7200
G.R(%)		8.92	7.84	5.15	3.56	2.63	2.38	2.24

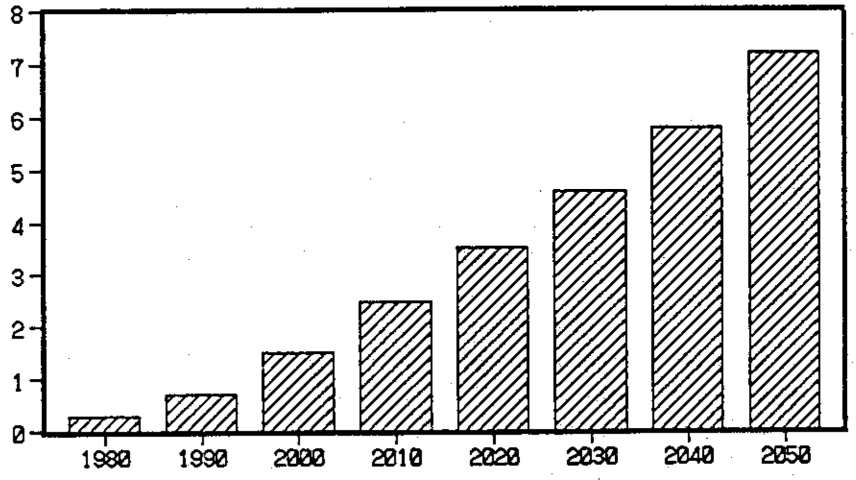

Fig. 3.3 China: GNP scenario
(Unit: 1000 Billion Constant 1980 US$)

3) **GNP Share by Sectors** In 1980 and 1990, the GNP shares by sectors are as following:

(1) Industry: 49.4% and 51.7%;
(2) Agriculture: 30.4% and 23.6%;
(3) Service: 16% and 19.6%;
(4) Transportation: 4.6% and 5.1%.

The evolution of China's economic structure is assumed as showing in Fig. 3.4.

3.2 Useful Energy Demand

3.2.1 Agriculture Sector

In this study, agriculture sector has been further disaggregated into the following two sub-sectors:

1) **I1: Agriculture Motors** This represents the motor power used for irrigation, land preparation, fishing and husbandry.

2) **I2: Agriculture Heating** Such as grain drying, greenhouse heating, etc..

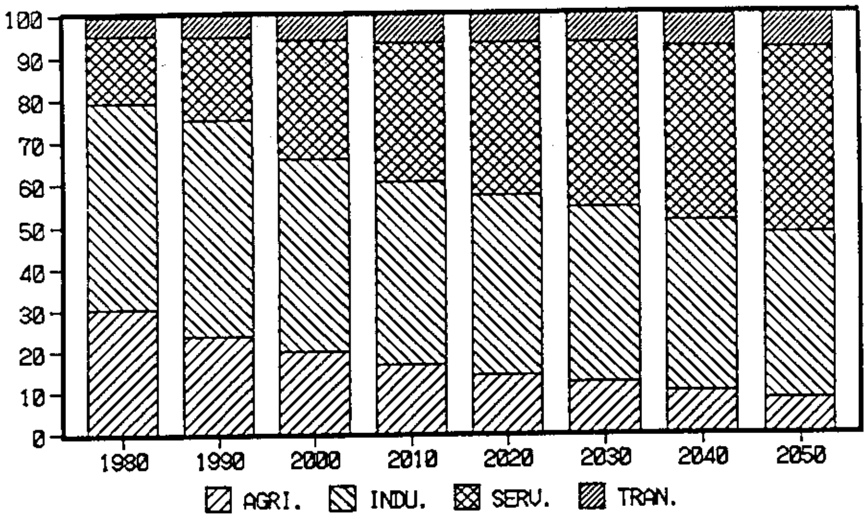

Fig. 3.4 China: Economic Structure in the Future

According to China' energy statistical data[1], the total final commercial energy consumed by agriculture sector in 1990 was 48.52 Mtce. About 3.6 Mtce coal are supposed to be used by industrial enterprises located in rural country which has been disaggregated and included into industry sector. And with the 0.1229 kgce/kwh used as the electricity conversion factor, the total final commercial energy used by agriculture sector can be accounted as 978 PJ in 1990.

Because the level of agricultural modernization in China is still low, the energy intensity also is very low in comparison with other countries. This study assumes that it will increased in the future in pace with China's agricultural modernization. The useful energy demand projection for agriculture sector is shown as follows:

Table 3.3 UED Projection: Agriculture Sector
(Unit: UED PJ, GNP Billion Constant 1980 US$, Intensity MJ/US$)

Year	1990	2000	2020	2050
Total	316	634	1164	1717
UED(I1)	239	513	956	1379
UED(I2)	77	121	208	338
Agri. GNP	166	300	494	576
Intensity	1.90	2.11	2.36	2.98

3.2.2 Industry Sector

Useful energy demand projection for industry sector has been made according to the following sub-sectors disaggregated in this study:

1)**I3--I5: Common Industry** This sub-sector represents the miscellaneous energy use in the industry sector except the following specific sub-sectors. Three kinds of devices are modelled in this sub-sector, i.e. motor, boiler and furnace.

2)**IK--IN: Chemical Industry** Non-energy use is included in this sub-sector, and also motor, boiler and furnace are modelled here.

3)**IA--IC: Iron and Steel Production** In this sector, the useful demand is expressed by the physical amount of crude steel production. The production process consists of iron making, steel casting and milling. For each stage, energy intensity is used to calculate the final energy demand.

4)**IX--IY: Cement Production** The physical amount of cement production is also used as the useful energy in this sector. The electricity and thermal energy demands are distinguished by two kinds of demand devices: motor and kiln. Energy intensity is used for final energy calculation.

5)**IP--IR: Paper Production** The representation of useful energy demand is same as above two sub-sectors. Electrical motor and boiler are modelled here for the electricity and thermal energy use separately.

The production projection of iron and steel, cement and paper is shown in Table 3.4.

Table 3.4 UED Projection: Physical Production
(Unit: Population Million, Production Mt, *Per capita* kg/p)

Year	1990	2000	2020	2050
Population	1143	1250	1410	1500
crude Steel	66.35	100.00	192.00	330.00
Per Capita	58	80	136	220
Cement	209.71	300.00	441.60	600.00
Per Capita	184	240	313	400
Paper	13.72	30.40	55.20	97.50
Per Capita	12	24	39	65

The useful energy projection for the common and chemical industry sub-sectors are listed as follows:

Table 3.5 UED Projection: Industry sub-sectors(Unit: PJ)

Year	1990	2000	2020	2050
Common	3359	4782	7975	12663
Chemical	2833	3834	5852	8179

3.2.3 Service Sector

In this study, the service sector includes the commercial and public services. Energy use only refers to that used by lighting and appliance (R1), space heating(R2), water heating (R3) and air conditioning (R4). Oil used for transportation which is included according to China's energy statistical data[1] in this sector, is separated into transportation energy consumption.

In 1990, the service sector accounted for 19.6% of the total GNP (except the contribution by transportation sector), and consumed 818 PJ of final energy which is about 2.8% of the total final energy use. The final energy intensity is 5.92 MJ/US$, i.e. about 0.22 kgce/US$. With the development of China's economy and the expanding GNP share of service sector, the energy consumption in this sector will also increase in the future. Table 3.6 shows the useful energy demand projection for the service sector.

Table 3.6 UED Projection: Service Sector
(Unit: UED PJ, GNP Billion Constant 1980 US$, Intensity MJ/US$)

Year	1990	2000	2020	2050
Total	442	1302	3807	9269
R1	70	211	973	3099
R2	249	601	1152	2558
R3	92	350	906	1493
R4	31	140	776	2119
Ser. GNP	138	420	1269	3168
Intensity	3.20	3.10	3.00	2.93

3.2.4 Residential Sector

This study deals with Urban and rural residential separately because of the different features of urban and rural residential energy use. For the urban residential sub-sector, lighting and appliance (RA), space heating (RB), water heating (RC), cooking (RD) and air conditioning (RE) are modelled to represent the different purposes of energy use. In the rural residential sub-sector, energy end use is classified into lighting and appliance (RF), space heating (RG) and cooking (RH).

1)**Urban Residential** In 1990, about 3070 PJ (104.89 Mtce) final energy was consumed by urban residential, and energy consumption ***per capita*** is 0.35 Mtce. The final efficiency was assumed to be 35.7%, so the useful energy ***per capita*** in 1990 was 3.63 GJ/P. In the future, the useful energy demand in the urban residential will increase with the increase of personal income and this study assumes that the useful energy ***per capita*** will be 8.25 GJ/P by urban residential in 2050. The useful energy demand by urban residential is listed in Table 3.7.

2)**Rural Residential** In China's rural country, because of shortage of commercial energy, the energy consumption ***per capita*** by residential is very low. Large amount of biomass such as firewood and crop stalks has been used by traditional stove with low efficiency which is about 10% at present. In 1990, about 7323 PJ biomass seamed to be used by rural residential, while the commercial energy use is 2445 PJ. The useful energy ***per capita per*** day is only 1010 Kcal.

Table 3.7 UED Projection: Urban Residential
(Unit: UED PJ, Population Million, *Per Capita* GJ/p)

Year	1990	2000	2020	2050
Total	1097	2363	5143	8664
RA	50	359	976	1903
RB	457	881	1729	3000
RC	218	431	980	1510
RD	356	549	1061	1474
RE	16	143	397	777
Population	302	450	818	1050
Per Capita	3.63	5.25	6.29	8.25

This study assumes that in the future the use of biomass will decrease to 2634 PJ in 2050 and the efficiency of traditional stove will increase to 30%. With the improvement of living condition in rural country, the useful energy ***per capita per day*** will rise to 1700, 2900 and 4100 Kcal in 2000, 2020 and 2050 respectively. Table 3.8 is the results of useful energy demand projection for rural residential.

Table 3.8 UED Projection: Rural Residential
(Unit: UED PJ, Population Million, *Per Capita* GJ/p)

Year	1990	2000	2020	2050
Total	1305	2072	2624	2830
RF	68	144	265	447
RG	593	978	1196	1234
RH	644	950	1163	1149
Population	841	800	592	450
Per Capita	1.55	2.59	4.27	5.79

3.2.5 Transportation Sector

In transportation sector, person-kilometers and ton-kilometers are used to represent the useful demand for two sub-sectors: passenger transport(T1) and freight transport(TA). Five kinds of devices are modelled in the passenger transport sub-sector: railway, automobile, bus, ship and airplane. In the freight transport sub-sector, five kinds of devices are modelled: railway, truck, ship, airplane and pipeline. The mode split of each sub-sector is given exogenously by the ADRATIO table of MARKAL.

1)**Passenger Transport** In 1990, the passenger transport turnover is 562.8 Bpkm and the pkm ***per capita*** is 492 km. In the past decade, the elasticity of passenger transport turnover vs. GNP is about 1.07. This study assumes that the elasticity will keep the constant value 1.0 in the future and the turnover projection is as follows:

Table 3.9 UED Projection: Passenger Transport
(Unit: UED Bpkm, Population Million, GNP Billion Constant 1980 US$)

Year	1980	1990	2000	2010	2020	2030	2040	2050
Population	987	1143	1250	1340	1410	1450	1480	1500
GNP/p	304	616	1200	1850	2500	3150	3900	4800
Growth Rate		7.32	6.90	4.42	3.06	2.34	2.16	2.10
Turnover	228	563	1198	1978	2813	3645	4607	5748
pkm/p	231	492	958	1476	1995	2514	3113	3832
Growth Rate		7.85	6.90	4.42	3.06	2.34	2.16	2.10
Elasticity		1.07	1.00	1.00	1.00	1.00	1.00	1.00

2)**Freight Transport** In this sub-sector, elasticity of freight transport turnover vs. GNP has been used for the projection. The results are listed in Table 3.10.

Table 3.10 UED Projection: Freight Transport
(Unit: UED Btkm, GNP Billion Constant 1980 US$, Intensity tkm/US$)

Year	1980	1990	2000	2010	2020	2030	2040	2050
GNP	300	705	1500	2479	3525	4568	5772	7200
Growth Rate		8.92	7.84	5.15	3.56	2.63	2.38	2.24
Turnover	1203	2621	5182	8563	12149	15750	19927	24855
Growth Rate		7.65	7.06	5.15	3.56	2.63	2.38	2.24
Intensity	4.01	3.72	3.50	3.50	3.50	3.50	3.50	3.50
Elasticity		0.91	0.90	1.00	1.00	1.00	1.00	1.00

4. ANALYTICAL RESULTS OF BASELINE CASES

For all assumed scenarios, the baseline projections are different only in the supply sector along with the different constraints of natural uranium resources. That means the results of supply sector in the P cases are same between scenario BASE1 and BASE3 with expanding nuclear power capacity, and same between scenario BASE2 and BASE4 with limited nuclear energy utilization. The baseline CO_2 emission projections are also different because of these differences. As for the demand side, all the four scenarios have the same trends. The detail results of the baseline projection are given in the following section.

4.1 Demand Sector

As mentioned above, the development of final energy consumption in the demand sector are same in the baseline projections among scenarios BASE1-BASE4. The final energy demand will increase from 29.34 EJ in 1990 to 85.96 EJ in 2050. Their average annual growth rate is 2.17%. In the sub-sectors, the share of energy use by service and transportation changes greatly from 2.79% and 6.24% in 1990 to 10.89% and 20.77% in 2050. The final energy consumption by sectors and energy types are shown in Fig. 4.1 and 4.2.

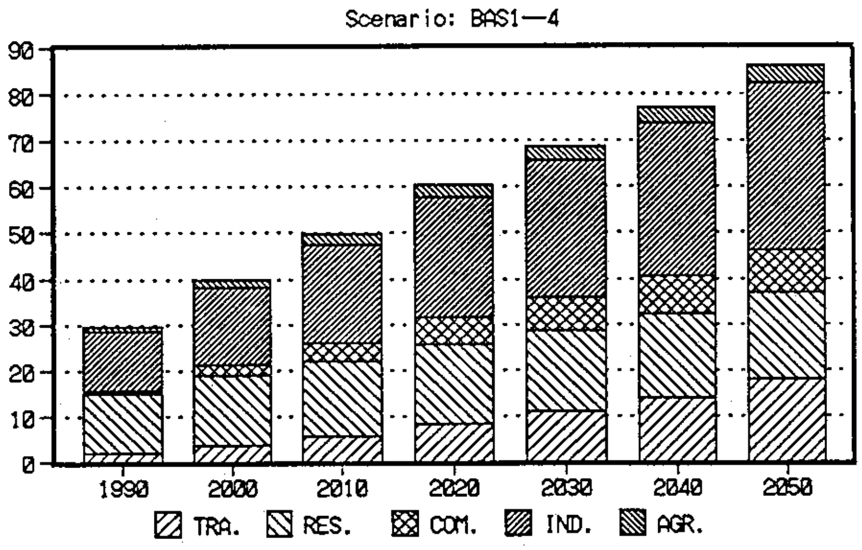

Fig. 4.1 Baseline Projection: Final Energy Consumption by Sectors(Unit: EJ)

4.2 Supply Sector

4.2.1 Primary Energy use

Primary energy use in scenario BASE1 and BASE3 is different from that in BASE2 and BASE4 by the different share of nuclear utilization.

In the scenario BASE1 and BASE3, the primary energy supply will increase from 37.46 EJ in 1990 to 137.4 EJ in 2050. The share of coal utilization will increase from

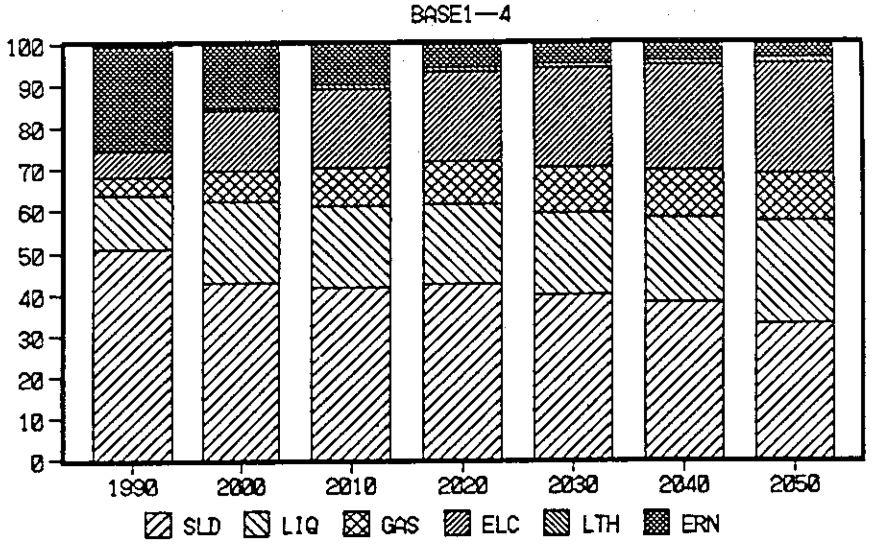

Fig. 4.2 Baseline Projection: Energy Type of Final Energy Use

60.2% in 1990 to 67.4% in 2050. The nuclear utilization will be 6.4% of the total primary energy in 2050.

In the scenario BASE2 and BASE4, the primary energy supply will be 138.48 EJ in 2050, and the share of coal and nuclear will be 72.7% and 1.3% in 2050.

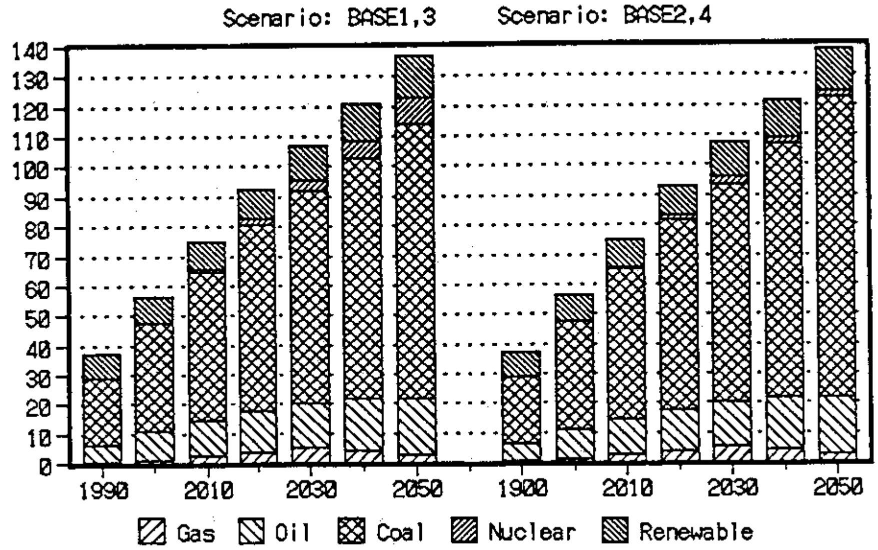

Fig. 4.3 Baseline Projection: Primary Energy Use(Unit: EJ)

4.2.2 Electricity Generation

Because of the electricity consumption in the final energy will increase from 6.3% in 1990 to 26.2% in 2050, the electricity generation will grow quickly in the future from 2.23 EJ in 1990 to 25.9 EJ in 2050. The coal fired power plants will still play the leading role while the oil and gas fired power plants lose the competition. For the nuclear power plants, it is limited not by the economic factor but the resources constraints, i.e.

supply of natural uranium is limited within indigenously available quantily. This causes the difference in the electricity generation between BASE1, BASE3 and BASE2, BASE4.

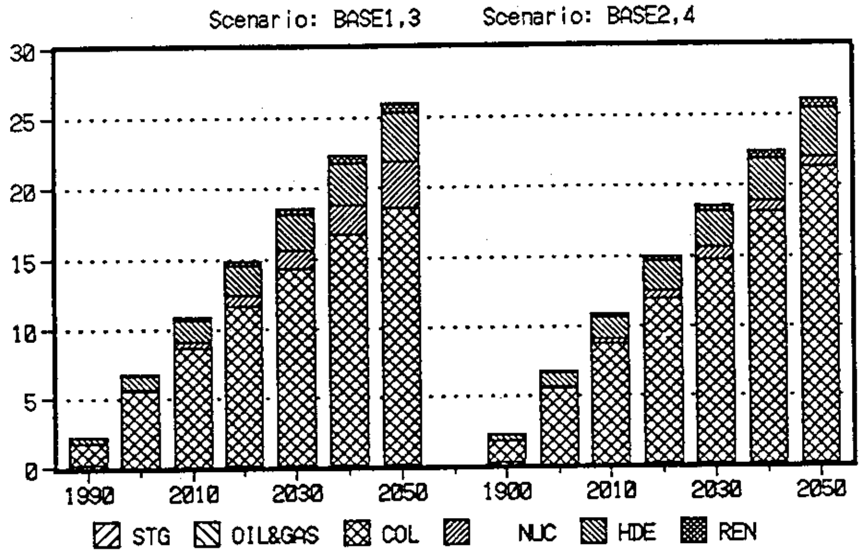

Fig. 4.4 Baseline Projection: Electricity Generation by Input(Unit: EJ)

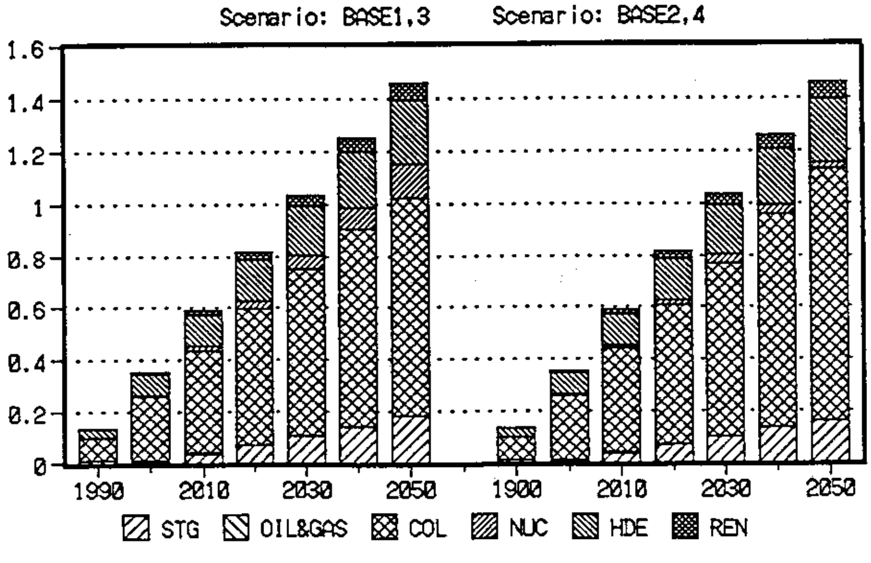

Fig. 4.5 Baseline Projection: Installed Capacity of Electricity Power Plants(Unit: TW)

4.3 Baseline CO_2 Emissions

As a result of increasing energy demands and continuing coal dominant energy structure, the China's CO_2 emission will increase in the next sixty years. The emission trends is presented in the Fig. 4.6. The total emission is 2.37 $BtCO_2$ in 1990 and will be 9.55 $BtCO_2$ in scenario BASE1, BASE3, 10.28 $BtCO_2$ in scenario BASE2, BASE4 in 2050.

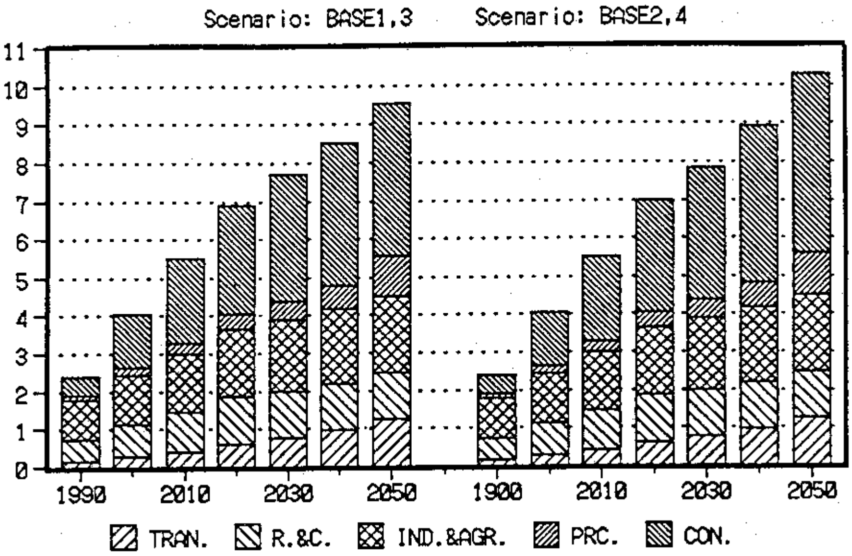

Fig. 4.6 **Baseline Projection: CO_2 Emission and Contributions of Sectors(Unit: Billion Ton CO_2)**

The evolution of CO_2 emission from different sectors is also shown in the above figure. The main increase of CO_2 emission comes from conversion sector of energy carriers, i.e. the electricity generation sector. In scenario BASE2, BASE4, because of no imported natural uranium, large amount of nuclear electricity in scenario BASE1, 3 is replaced by coal power plants. The emission is 0.73 $BtCO_2$ more than that of scenario BASE1, BASE3 in 2050.

4.4 Scenarios Indicators

The Table 4.1 gives several important scenario indicators of the P case's results.

Table 4.1 Baseline Projection: Scenarios Indicators

Year	1990	2000	2010	2020	2030	2040	2050
BASE1, BASE3:							
TPE/GNP(MJ/US$)	53.13	37.67	30.35	26.31	23.49	21.02	19.08
FE/GNP(MJ/US$)	41.61	26.66	20.18	17.13	15.10	13.39	11.94
CO_2 *per capita*(t)	2.08	3.26	4.12	4.85	5.35	5.8	6.37
CO_2 *per* GNP(kg/US$)	3.37	2.72	2.23	1.94	1.70	1.49	1.33
BASE2, BASE4:							
TPE/GNP(MJ/US$)	53.13	37.67	30.38	26.35	23.54	21.12	19.23
FE/GNP(MJ/US$)	41.61	26.66	20.18	17.13	15.10	13.39	11.94
CO_2 *per capita*(t)	2.08	3.26	4.14	4.90	5.43	6.05	6.85
CO_2 *per* GNP(kg/US$)	3.37	2.72	2.24	1.96	1.72	1.55	1.43

4.5 CO_2 Intensity of Primary Energy Use

4.5.1 Fossil Fuel Share and Mix

In 1990, the fossil fuel share of total primary energy consumption is 77.3%, and it will rise to 83.6% in the scenario BASE1, 3 and 88.8% in the scenario BASE2, 4 in 2050.

Table 4.2 Baseline Projection: Fossil Fuel Share of Primary Energy Consumption(Unit: %)

Year	1990	2000	2010	2020	2030	2040	2050
BASE1, BASE3	77.3	83.9	86.2	87.3	86.2	85.3	83.6
BASE2, BASE4	77.3	83.9	86.6	87.9	87.3	87.9	88.8

The fossil fuel mix is shown in Fig. 4.7.

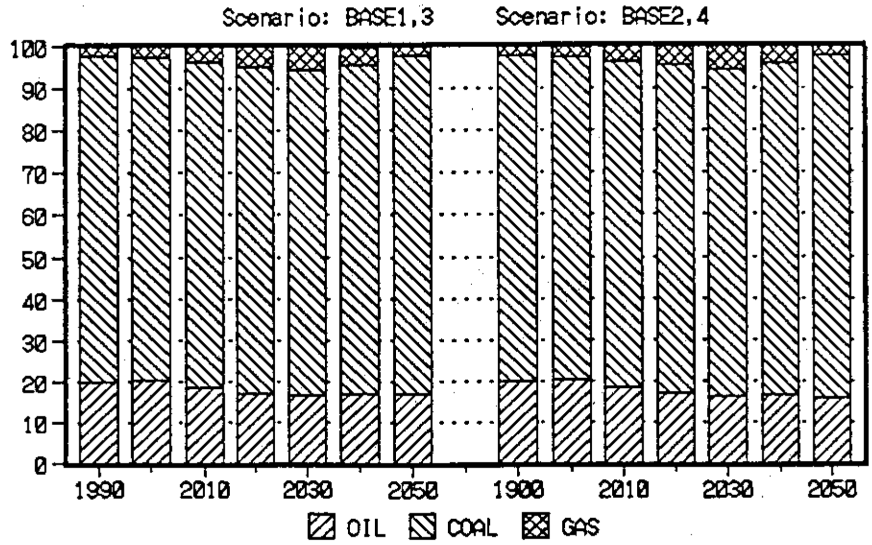

Fig. 4.7 Baseline Projection: Fossil Fuel Mix

4.5.2 Nuclear and Renewable

In the P case, the nuclear energy use is constrained mainly by the natural uranium resources. Both LWR and VHTR can be selected by MARKAL, but the LMFBR has no economic competition. In the scenario BASE1, BASE3 where imported natural uranium is available, the LWR reaches the upper-bound 30 GW in 2020 and 132 GW in 2050. The VHTR reaches the upper-bound 10 GW in 2050. In the scenario BASE2, BASE4 with no imported natural uranium, the LWR will grow to 37 GW in 2030 and then is decreasing to 24 GW in 2050 while the VHTR reaches the upper-bound 10 GW in 2050.

For the renewable energy utilization, the traditional fuel of biomass will decrease by the exogenous constraint. The hydraulic power increases from 36 GW in 1990 to 243 GW in 2050 according to China's energy planing. The other commercial renewable energy (geothermal, solar, wind, etc.) assumed to be 1064 PJ in 2020 and 2186 PJ in 2050.

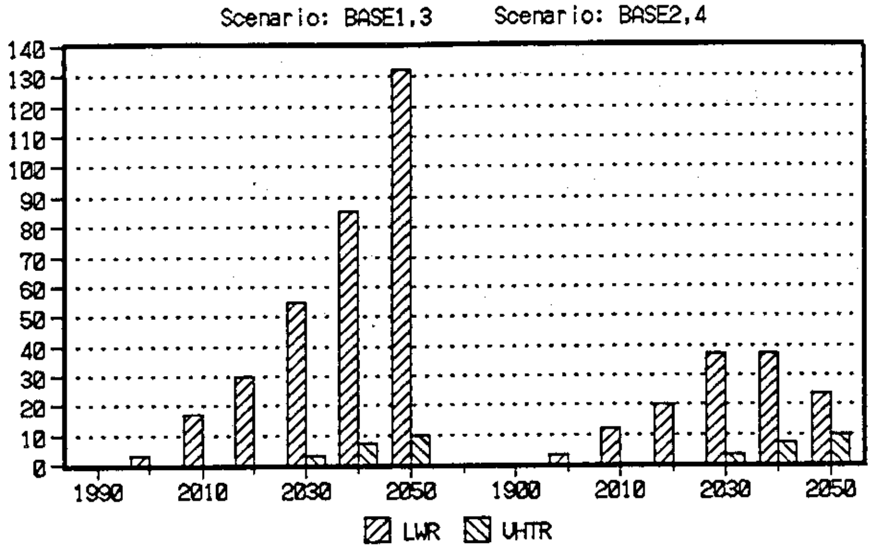

Fig. 4.8 Baseline Projection: Nuclear Energy Use(Unit: GW)

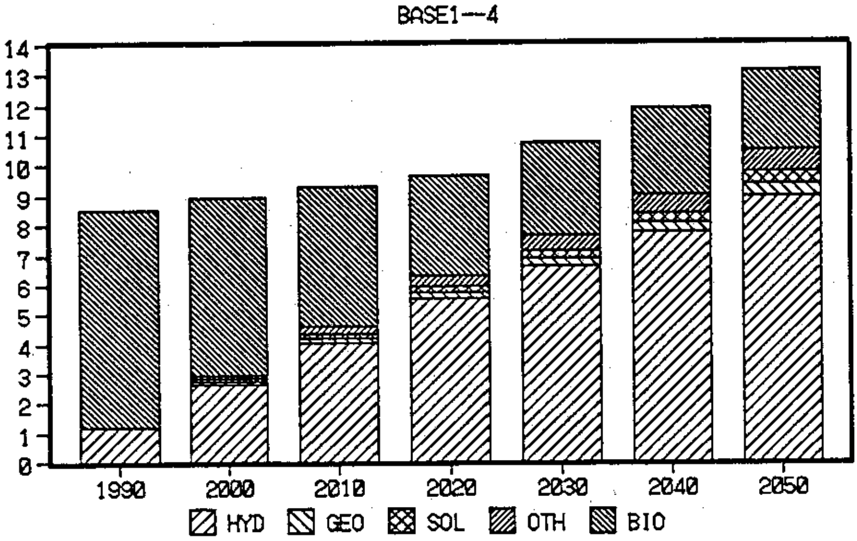

Fig. 4.9 Baseline Projection: Renewable Energy Use(Unit: EJ)

4.5.3 CO_2 Intensity of Total Primary Energy

The CO_2 intensity of primary energy is given in Table 4.3.

Table 4.3 Baseline Projection: CO_2 Intensity of PE(Unit: $ktCO_2/PJ$)

Year	1990	2000	2010	2020	2030	2040	2050
BASE1,3	63.36	72.09	73.35	73.76	72.24	70.81	69.49
BASE2,4	63.36	72.09	73.74	74.40	73.24	73.42	74.24

5. CO_2 EMISSION REDUCTION

5.1 Overview

5.1.1 Maximum Reduction

For all scenarios, the profiles of CO_2 emission reduction as the results of E cases and M cases, compared with P cases are shown in Fig. 5.1.

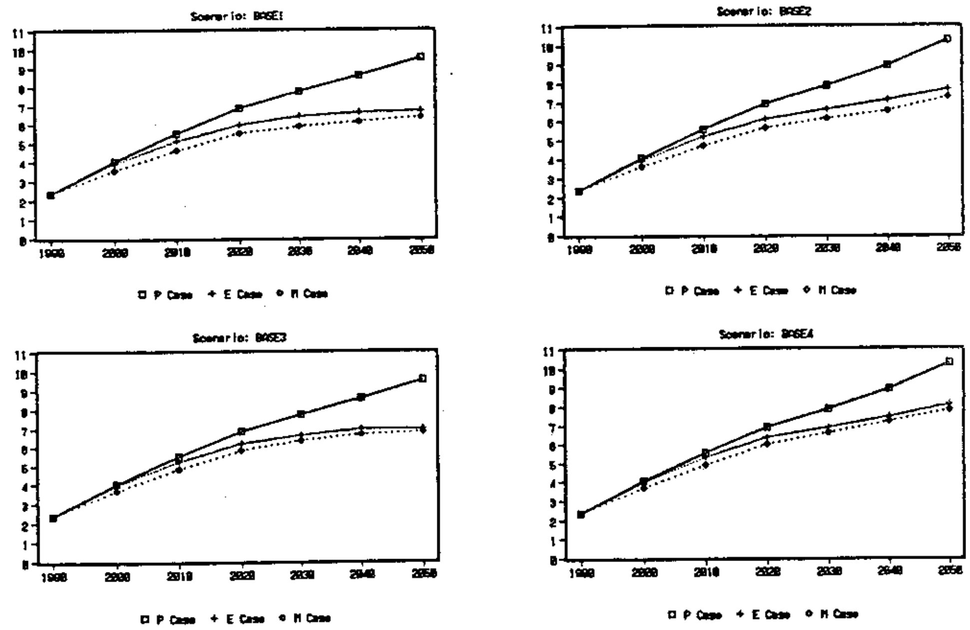

Fig. 5.1 Overview of CO_2 Emission Reduction(Unit: $BtCO_2$)

The maximum CO_2 reduction occurs in the M case of scenario BASE1, i.e. from 9.55 $BtCO_2$ to 6.39 $BtCO_2$ in 2050. The net reduction is 3.16 $BtCO_2$ which is almost 1.3 times as much as the emission in 1990. For the scenarios BASE2-4, the net CO_2 reduction is 3.03, 2.72 and 2.44 $BtCO_2$ respectively. In the following sections, scenario BASE1 is selected to analyze changes of the energy system due to the CO_2 reduction. Because M case uses the cumulative CO_2 as the objective function and the results have no economic meaning, the comparison has been made between P case and E case.

5.1.2 Changes of Scenarios Indicators

When CO_2 emission is reduced, all major indicators of the scenarios will be changed. The comparison of this change in 2050 of P case and E case in scenario BASE1 is shown in Table 5.1.

Table 5.1 Changes of Scenarios Indicators in 2050

Cases	TPE/GNP(MJ/US$)	FE/GNP(MJ/US$)	CO_2/GNP(kg/US$)	CO_2/Capita(t)	Fossil Fuel Share(%)	CO_2/TPE(kt/PJ)
P	19.08	11.94	1.33	6.37	83.6	69.49
E	17.29	11.10	0.93	4.48	70.1	53.96

5.2 BASE1: Supply Sector Impacts

5.2.1 Primary Energy Supply

Primary energy consumption decreases from 137.4 EJ to 124.4 EJ in 2050 when the case changes. About 9.4% of the primary energy is saved in the E case. In 2050, the share of Coal utilization in the primary energy is 34.3% in the E case compared with 67.4% in the P case. Coal is substituted by oil and gas, nuclear and renewable energy resources.

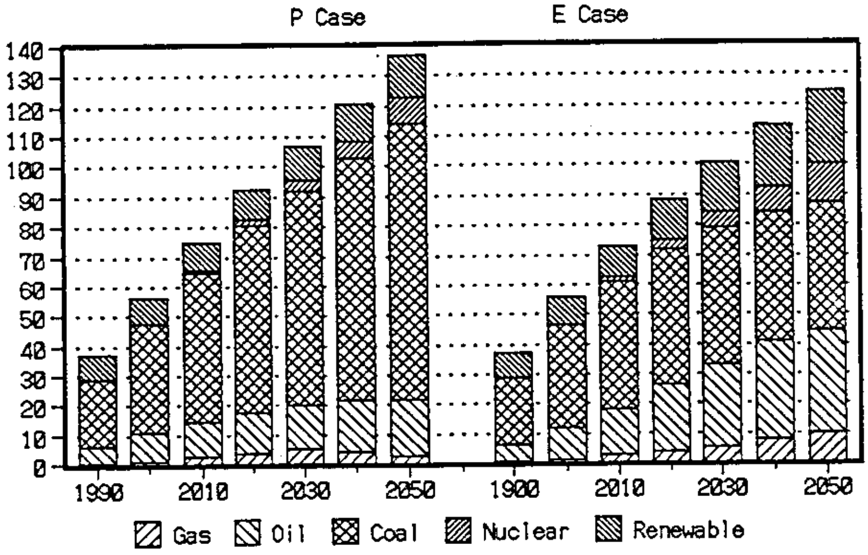

Fig. 5.2 BASE1: Changes of Primary Energy Use(Unit: EJ)

5.2.2 Electricity Generation

In the E case of scenario BASE1, the coal fired electricity decreases from 71.1%

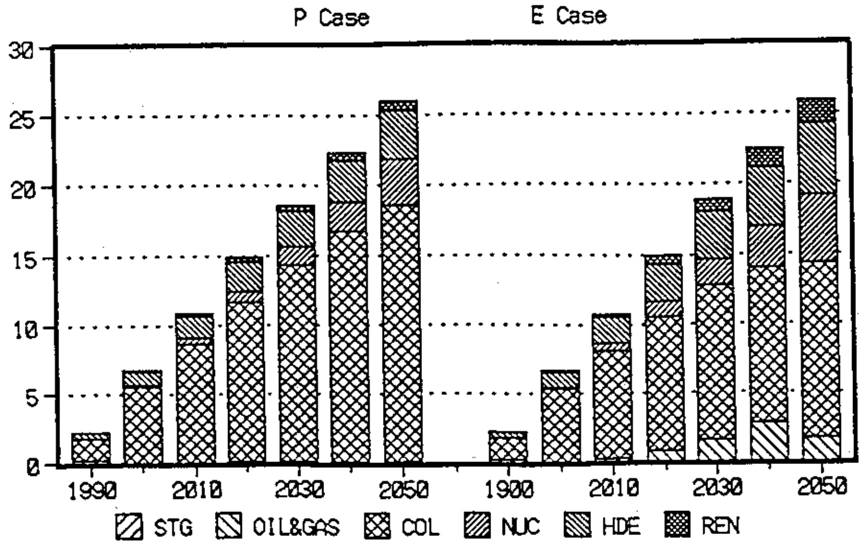

Fig 5.3 BASE1: Changes of Electricity Generation(Unit: EJ)

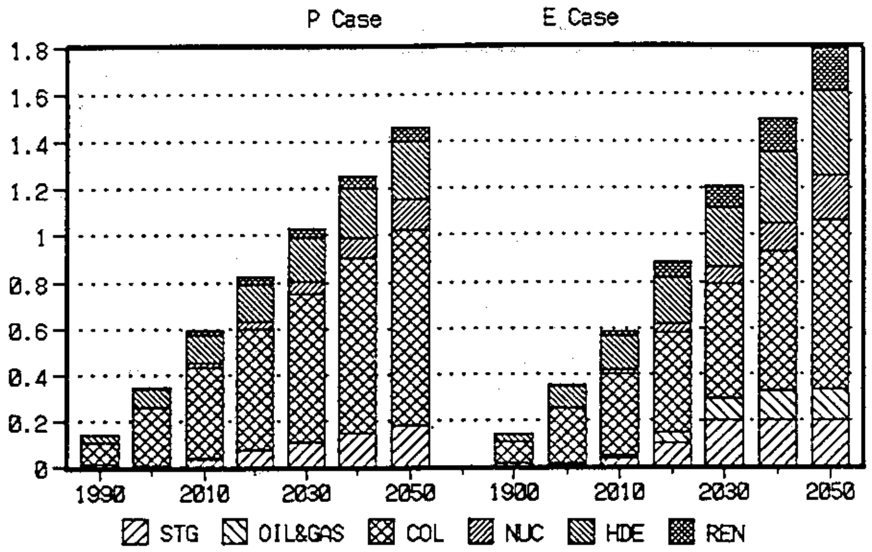

Fig. 5.4 BASE1: Changes of Installed Capacity of Electricity Power Plants(Unit: TW)

in the P case to 48.6% in 2050. In the same year the nuclear power and hydraulic power increase from 12.9% and 13.3% in the P case to 18.9% and 19.7% in the E case respectively. Oil and gas, the other renewable power also increase in the E case.

5.2.3 Nuclear and Renewable Energy

Both nuclear and renewable energy increase in the E case of scenario BASE1. The results are compared in Fig. 5.5 and Fig. 5.6. For the nuclear, LMFBR is selected in the E case with the capacity 40 GWe in 2050. The increase of LWR is contributed by the technology of LWR co-generation. The total nuclear utilization of E case is 202 GW in 2050.

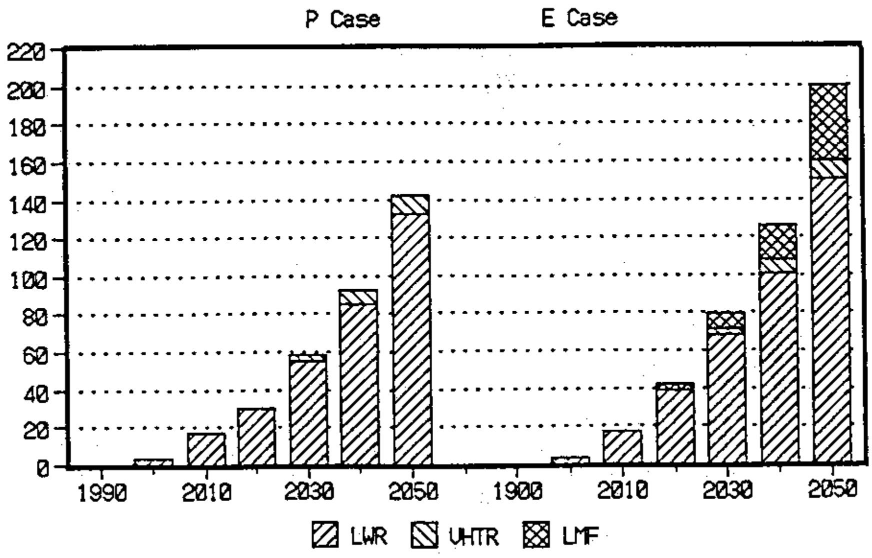

Fig 5.5 BASE1: Changes of Nuclear Utilization(Unit: GW)

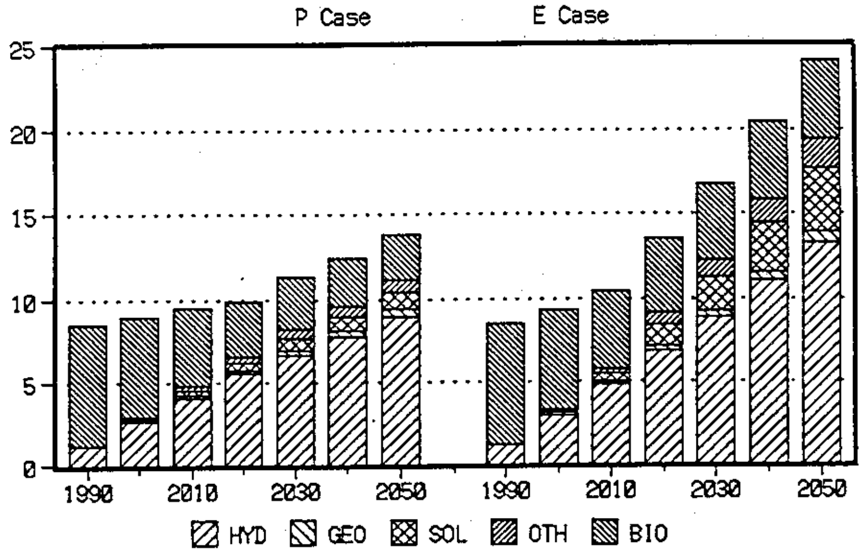

Fig. 5.6 Changes of Renewable Energy Utilization(Unit: EJ)

As to the utilization of renewable energy, the hydraulic power reaches the upper-bound 360 GW in 2050 in the E case. The other renewable energy such as solar, geothermal, commercial biomass, etc. also increases in the E case. The total utilization of renewable energy is 24.0 EJ in 2050, about 19.3% of the total primary energy.

5.3 BASE1: Demand Sector Impacts

5.3.1 Final Energy Consumption

The final energy consumption decreases to 79.9 EJ in the E case from 86.0 EJ in the P case in 2050. The liquid and gaseous fuels expand from 36.0% to 50.9%

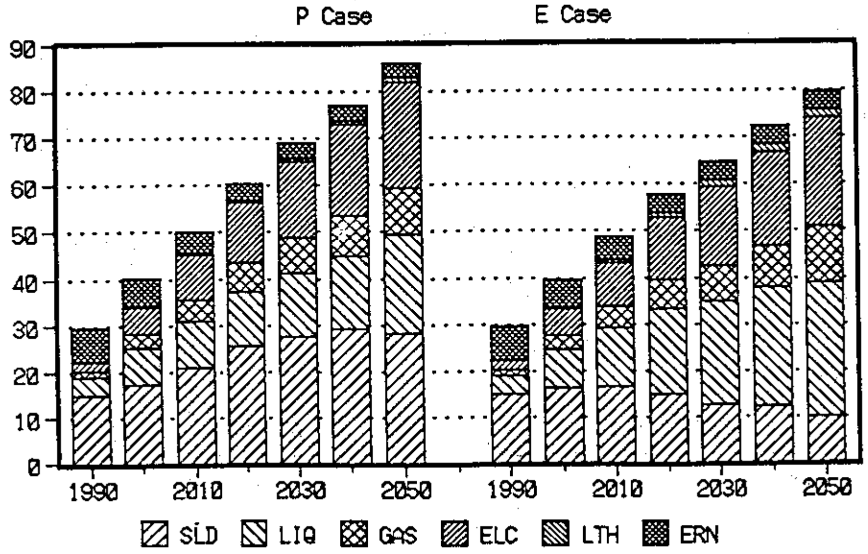

Fig. 5.7 BASE1: Changes of Final Energy Consumption(Unit: EJ)

while the solid fuels decrease from 33.0% to 12.5% in 2050. The use of electricity and heat increases from 27.3% to 31.0%. Fig. 5.7 shows the comparison.

5.3.2 Sectoral Fuel Mix

Sectoral final energy consumption and fuel mix of agriculture and industry, service and residential, transportation are shown in Fig. 5.8, 5.9 and 5.10.

The final energy consumption by agriculture and industry does not change greatly

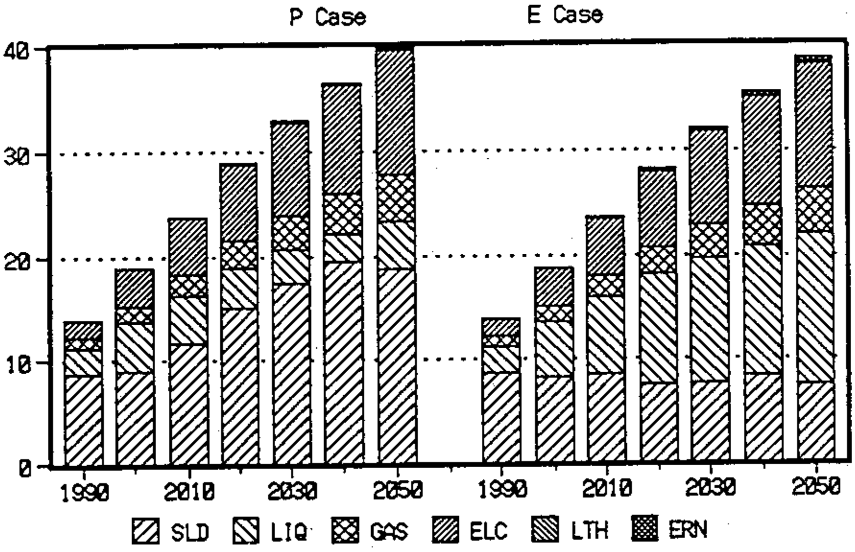

Fig 5.8 BASE1: Changes of Final Energy use and Fuels Mix by Agriculture and Industry(Unit: EJ)

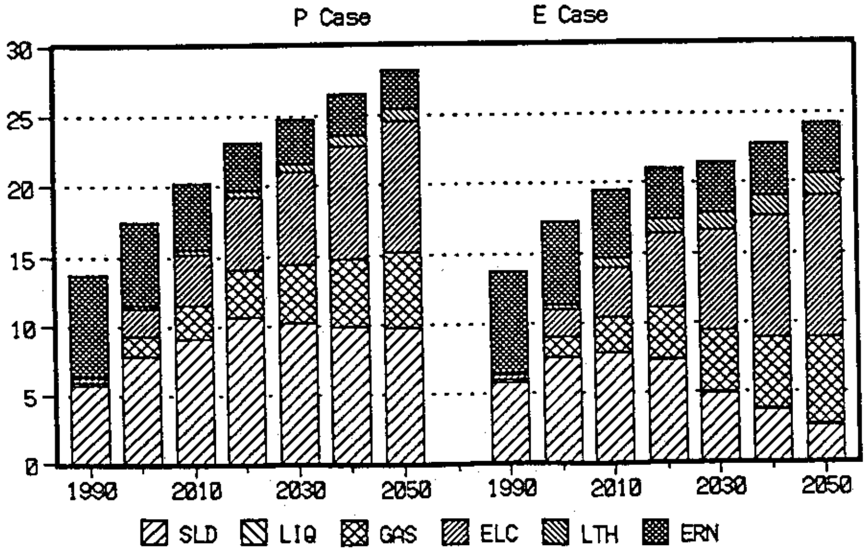

Fig. 5.9 BASE1: Changes of Final Energy Use and Fuels Mix by Service and residential Sector(Unit: EJ)

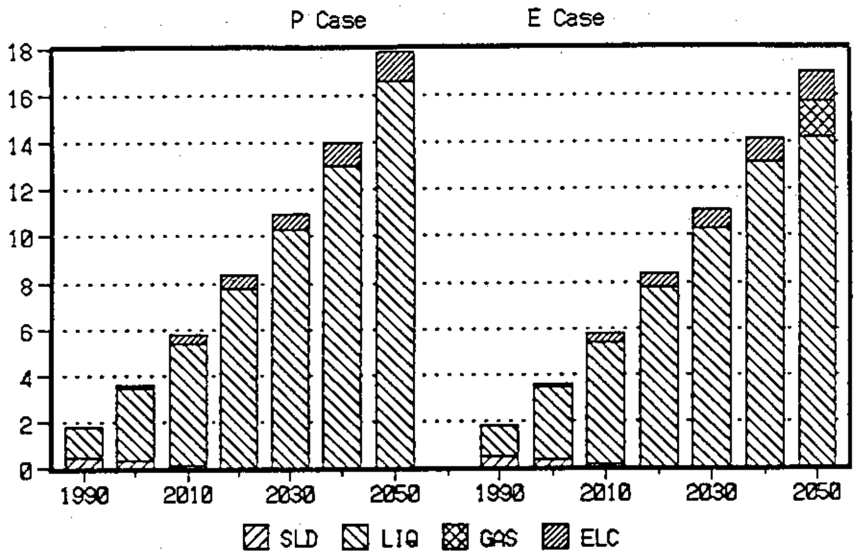

Fig. 5.10 BASE1: Changes of Final Energy Use and Fuels Mix by Transportation Sector(Unit: EJ)

except for some fuel switching from liquid to solid. In the service and residential sector, the total final energy consumption decreases largely from 28.3 EJ of the P case to 24.1 EJ of the E case in 2050. Solid fuels are replaced by electricity, heat, and gaseous fuels. The transportation sector will continue to depend on the liquid fuels even in the E case, except for gas fuel in 2050.

5.4 Tradeoff Between Cost and Emission

Tradeoff relationship between discounted system cost and CO_2 emission is analyzed by this study. The tradeoff relationship analysis use the following function as the objective function:

$$OBJ = PRICE + C(n) \times ENVCDE$$

with PRICE: Total Discounted System Cost
ENVCDE: Total CO_2 Emission

C(n) is the weight of CO_2 emission relative to the system cost, and can be interpret as the marginal cost of total CO_2 emission reduction. In this study, six cases, i.e. P1–P6 are analyzed and the corresponding values of C(1)–C(6) are 1, 3, 10, 25, 50, 100 US\$/TCO_2. P case can be regarded as a case with C(0)=0 US\$/TCO_2 compared with above cases. The results are shown in Fig. 5.11.

From P case to P1 case, with a low marginal cost of total CO_2 emission reduction, i.e. 1 US\$/TCO_2, the total CO_2 emission can be reduced 9.6% form 418 $BtCO_2$ to 378 $BtCO_2$. The total discounted system cost increases only 0.09% from 11115.9 BUS\$ to 11130.3 BUS\$.

From P1 case to P6 case, the total CO_2 emission can be reduced 13.2% from 378

$BtCO_2$ to 328 $BtCO_2$ with a high marginal cost of total CO_2 emission reduction, i.e. 100 US\$/TCO_2. The total discounted system cost increases 5.8% from 11130.3 BUS\$ to 11777.8 BUS\$.

This figure indicates that large amount of CO_2 emission reduction is possible with a low marginal cost of total CO_2 emission reduction, but the unit CO_2 emission reduction cost will becomes higher if CO_2 emission reduction is taken more severely.

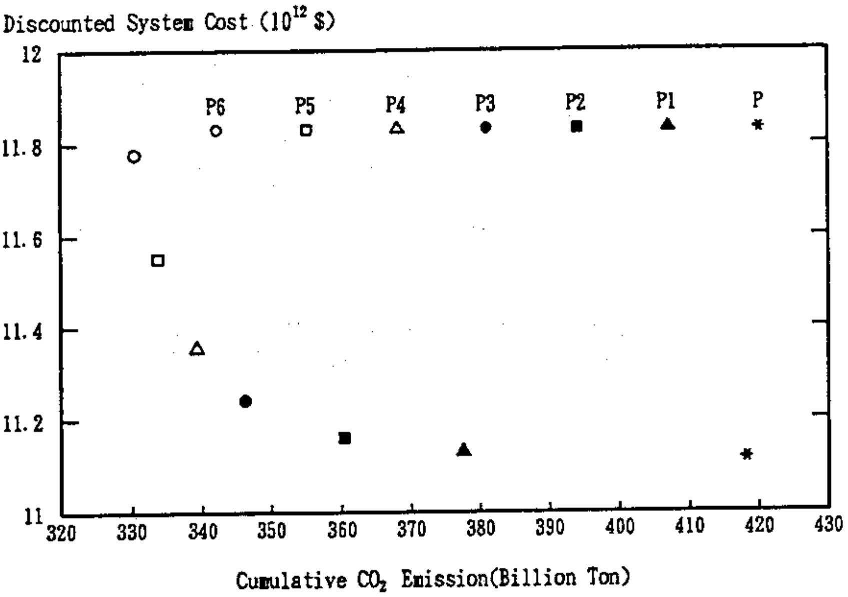

Fig. 5.11 BASE1: Tradeoff Relationship between Cost and Emission

The CO_2 emissions by sectors from case P-P6 in 2020 and 2050 is shown in the Fig. 5.12, 5.13.

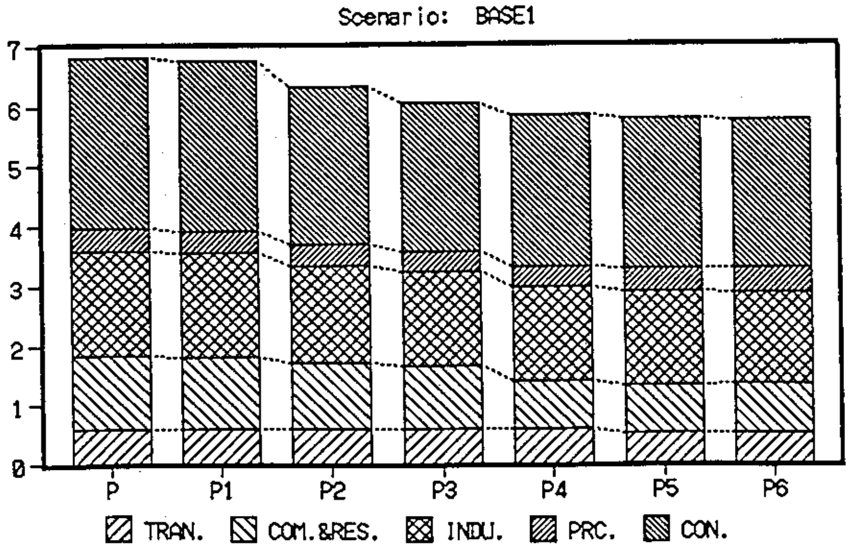

Fig. 5.12 BASE1: CO_2 Emissions by Sectors of Case P-P6 in 2020(Unit: Billion Ton CO_2)

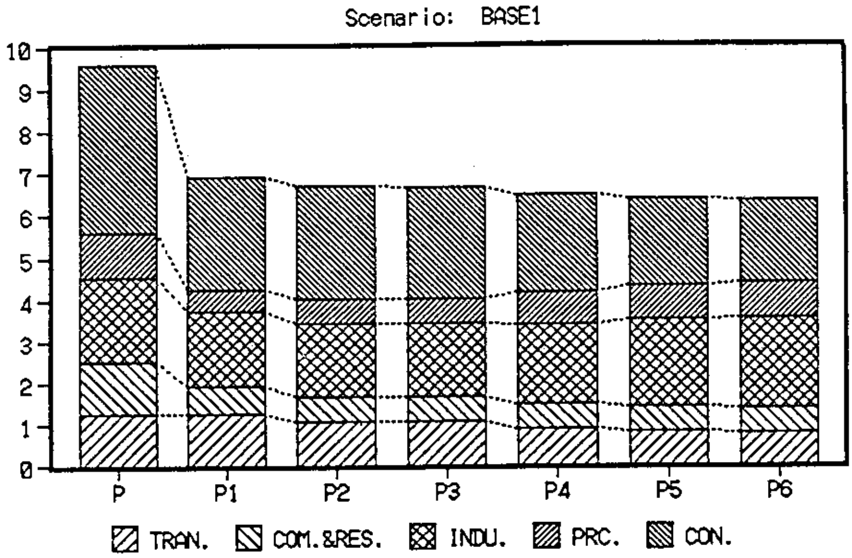

Fig. 5.13 BASE1: CO_2 Emission by Sectors of Case P-P6 in 2050(Unit: Billion Ton CO_2)

6 CONCLUSIONS AND DISCUSSION

By using MARKAL model, the study has made analyses on China's energy system and it's CO_2 emission reduction. MARKAL is a bottom-up model which takes a disaggregate approach to modelling energy system from supply side to demand side, considering many individual alternatives and their costs. It describes the impacts of such alternative investments on energy supply and demand through scenario analyses with possible and potential futures. Bottom-up approach focuses on the demand for energy services first, which can be satisfied finally through an integrated analyses of supply and demand in energy system. Bottom-up approach aims at a solution: usually the least-cost strategies for providing specified energy services. Applied to the greenhouse gases problem, they answer the question: How much it will cost to reduce greenhouse gases emission[16]. MARKAL is a powerful tool for developing least-cost national energy strategies and analyzing energy and environment issues.

The annual CO_2 emission from national energy system can be calculated by the Prof. Kaya formula:

$$CO_2 = CAPITA \ X \ \frac{GNP}{CAPITA} \ X \ \frac{TPER}{GNP} \ X \ \frac{TFOS}{TPER} \ X \ \frac{CO_2}{TFOS}$$

with CAPITA: Population
GNP : Gross National Production
TPER : Total Primary Energy Requirement
TFOS : Fossil Primary Energy Consumption

From above formula, we can see the total amount of CO_2 emission from the national energy system is determined by the social, economic, energy factors and environmental through technologies. The population and GNP are external to the MARKAL model, so the GNP/CAPITA is independent of the model. The TPER, TFOS and CO_2 are calculated by the MARKAL model.

Also the obvious measures for CO_2 emission reduction can be derived from this formula:

1)Reduce the amount of primary energy consumption ***per*** unit of GNP;
2)Reduce the share of fossil energy in the total primary energy consumption;
3)Reduce the average CO_2 emission ***per*** unit of fossil energy.

China's future energy consumption will increase in order to power her social and economic development. The primary energy mix is determined by the energy resource and technology utilization structure. The CO_2 emission will continue to increase even under the emission constraints in China's energy system. But the CO_2 emission ***per capita*** will only be 6.37 tCO_2 in the P case of scenario BASE1 and 4.48 tCO_2 in the E case of scenario BASE1 in 2050, which are very lower compared with those of industrialized countries.

The energy conservation and efficiency improvements shows a great deal of contribution to CO_2 emission reduction in this study. The total primary energy consumption *per* unit of GNP in the P case of scenario BASE1 will decrease from 53.13 MJ/US$ in 1990 to 19.08 MJ/US$ in 2050, and can be reduced in the E case of scenario BASE1 to 17.29 MJ/US$ in 2050. For the final energy use *per* unit of GNP, in the P case of scenario BASE1 it will decrease from 41.46 MJ/US$ in 1990 to 11.94 MJ/US$ in 2050. In the E case, it will decrease to 11.10 MJ/US$ in 2050.

The nuclear and renewable energy will play important roles in the CO_2 emission reduction. The total share of nuclear and renewable energy in the total primary energy consumption increase from 16.4% in the P case of scenario BASE1 to 29.7% in the E case of scenario BASE1 in 2050. If taking into account of the limited resources capacity of hydraulic power and the realistic utilization of other renewable resources, then the role of nuclear energy in the CO_2 emission reduction is irreplaceable in the future for China.

The role of fuels switching from coal to oil and gas is limited because oil and gas resources constraints in this study. And large amount of fuels switching from coal to oil and gas is unrealistic for China. From this point of view, the technology substitution by introducing nuclear and renewable energy technologies become more important for China in the CO_2 emission reduction.

This report gives a overall profile of China's energy-related CO_2 emission and its control strategies and is the first study by using MARKAL model to investigate the CO_2 issue in China's energy system to the year of 2050. The results depend on assumptions about future fuels price, discount rate, projection of useful energy demand and the flexibility of the modelled China's Reference Energy System. Sensitivity analysis is useful for understanding of China's energy development and its CO_2 problem. Because of author's limited available time in JAERI and data sources, the following idea of further researches can not be realized but is necessary for the future study:

1)Improvement on the Database of China's Reference Energy System: As the MARKAL model is a demand push model. Its accuracy of analytical results depends much on the database of each technology and useful demand projection. For the ETSAP's countries, they already have more than one decade's experience in improving on their databases. If we want to use MARKAL to formally analyze China's energy system, a more accurate, consistent and high quality database is important. In this report, the cost of CO_2 emission reduction have not been analyzed in detail for the reason of data's availability. In order to accurately estimate the cost of CO_2 emission reduction in China's energy system, the data of energy carriers' prices and costs of technologies should be evaluated in more accurate, consistent detail.

2)Reviewing Options to Reduce CO_2 Emission: According to the obvious measures for CO_2 emission reduction derived from above formula, there are a lot of technological options which can be analyzed by using models of the MARKAL type. They can be selected as the following ways:

a. Represented as the technological process in MARKAL model;
b. Different exogenous assumptions in the different scenario;
c. Sensitivity analysis performed in variant cases.

In this study, the options like additional savings the end-use sectors, recycling of carbonaceous material, CO_2 removal from electricity generation plants, etc., have not been modelled in China's Reference Energy System. These options should be taken into account in the case of vigorous emission reduction and their costs can be compared with other choices.

3)Analysis on the Impacts of CO_2 Emission Reduction Strategies on China's Economic Development: There are many macro-economic impacts of the CO_2 reduction strategies such as additional cost for implementation of CO_2 reduction measures, impacts on capital investment and the effects on the level of energy demand. Now it is possible to make such analysis by using hard-linked MARKAL-MACRO model[12] or MARKAL-MACROEM model[20]. This will be more meaningful to China because the most important thing is to minimize the effects on her economic development while reducing CO_2 emission.

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This report would not have been possible without the author's one year assignment at the Energy System Assessment Laboratory in Tokai Research Establishment of Japan Atomic Energy Research Institute(JAERI) under the STA(Science and Technology Agency of Japan) Scientist Exchange Program from March 30, 1993 to March 29, 1994 with the research subject: Strategy Analysis of CO_2 Emission Reduction by Using Nuclear Energy. I would like to offer my sincere gratitude to Dr. S. Yasukawa, the head of the Energy System Assessment Laboratory for suggesting the half year's extension of my assignment period to the original half year's schedule and STA's continuing financial support with the subsistence allowance to my extension.

I must express my appreciation of the special assistance given to me by my two cooperative scientists Dr. S. Yasukawa and Mr. O. Sato. Their research style and experience in the field of energy system analysis is very useful to me. I also thanks the other members of the staff in the Energy System Assessment Laboratory for their help and patience. Both professionally and personally, I have enjoyed my association with them.

My research assignment in JAERI was also supported by China Institute of Nuclear Industry Economics, especially by the president Zhen Yuhui. Without his understanding and encouragement to my external duration in JAERI and help in providing the necessary information on my research, it would be difficult for me to finish this study.

Most importantly, I want to dedicate this report to my wife, Liu Wenjing, who has patiently waited one year for me to complete my research work abroad just after we were married in February, 1993.

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