

Multi-regional Asian Energy/Environment/Resource Distribution Model for the Evaluation of Technology Strategies

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Introduction

Energy consumption in Asian countries is still increasing rapidly as the economic growth of this region recovers the trend in the 1990s. Environmental pollution issues also appear more seriously as the emission of pollutants from fossil fuel combustion increases. In Asian countries, coal supplies around 45% of the primary energy and will still be a high priority resource in the near future because of high availability and low supply costs. However, coal burning has two major problems: firstly, as is well known, coal burning has caused serious air pollution and health effects since the sulfur content of coal is higher than other fuels. Although desulfurization equipments have already been developed, they are not used well in Asian countries because of their high capital and operating costs. Secondly, like other fossil fuel resources, coal resources are unevenly distributed in Asian countries. They are mainly produced in inland areas while industry and urban areas are often developed in the coastal area. Transportation of coal between production and consumption regions requires considerable energy demand especially in China and India. Furthermore, the quality of coal, e.g. the contents of sulfur, sand, ash, calorie, etc., also ranges broadly. So called “clean-coal technologies” have positively been developed to overcome such problems.

Oil demand in Asian countries is also increasing as the demand for transportation sector grows. Because oil production capacity in Asian region cannot meet the increasing demand, it is projected that the 90% of oil supply of this region will depend on middle-east countries in the near future.

Recently, natural gas resources are focused on as the major energy sources by many countries. It is because low sulfur contents, availability of pipeline transportation, and high conversion efficiency in electric power generation by combined gas turbines. However, uncertainties still remain in the estimation of natural gas resources. Other renewable energy resources, e.g. wind power, solar and biomass, will also contribute to sustainable energy supply.

Global warming mitigation has also become international agreement after Kyoto Meeting in 1997 (COP3). In spite of the fact that many Asian developing countries have not agreed with the reduction target of the greenhouse gas emissions, they do not totally oppose the flexibility measures in Kyoto Protocol. Clean Development Mechanism (CDM) will promote the international collaboration on GHG emission reduction.

The above backgrounds suggest that the energy strategy is one of the highest priority policy issues and that the detailed regional characteristics should be involved concretely when we assess the

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resource and technology strategies in Asian countries. The purpose of this study is to develop multi-regional energy and environment model disaggregating two major Asian countries - China and India – into subregions. Domestic energy transportation is also dealt with explicitly in the model.

1. Background of Asian Energy Issues

Asian region has succeeded in rapid economic growth especially in 1980s. Asia-NIES countries already initiated the economic growth in the mid of 1970s followed by ASEAN countries and China in 1980s. India took off in 1990s. The annual economic growth rate of Asian region for 1985-1995 was 6.60% while that of world total was 2.52% in the same period. Although the “financial crisis” in 1997 affected the past trend seriously, Asian countries are still expected to recover their economic growth.

The demographic issues in Asian countries are still apparent. The population in Asian region was 1.4 billion in 1950 and has increased to 3.4 billion in 1995. In 2050, it will reach 5.4 billion according to the UN estimates.

Figure 1 exhibits the historical trends of annual primary energy demand growth rates. The energy consumption in Asian region has increased at 5.9% per year for 1971-1994 which is around 2.7 times of world average growth rate. The total energy consumption in Asian region comes to 1.5 billion tons of oil equivalent (GTOE) in 1994 which is 18.3% of total world energy consumption. On the contrary, per capita energy consumption in Asian region still remains at 6.5% of that in North America. The above high economic growth rates, high population growth rates and current low per capita energy

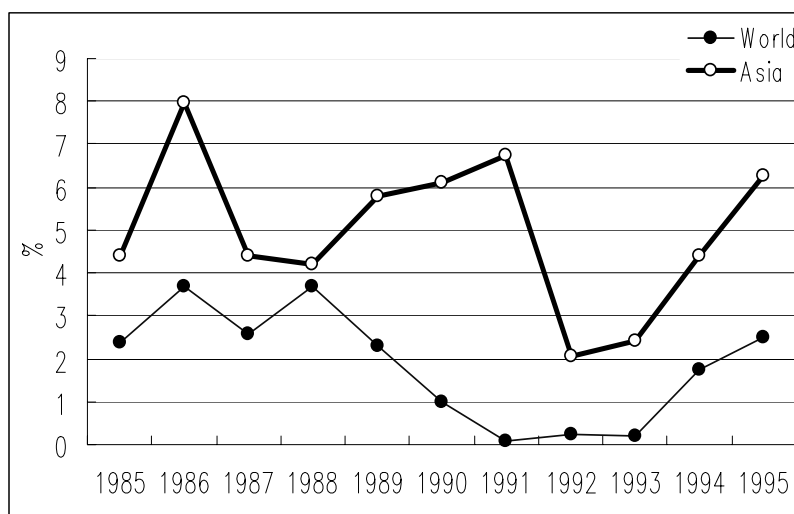


Figure 1 Historical trends of annual primary energy growth rates in the world and Asia

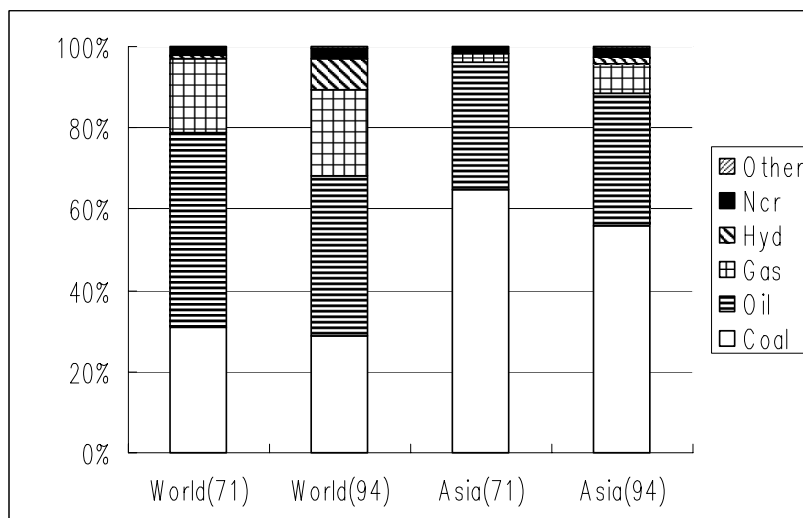


Figure 2 Primary energy supply mix of Asia and World in 1971 and 1994

consumption level suggest that the future energy demand in this region will increase enormously.

Figure 2 shows the primary energy supply mix of world total and Asia in 1971 and 1994. The

fraction of coal is around 56% in 1994. Although coal burning could cause serious environmental pollution, it will still be a main role in this region for the electric power generation because of its abundant resource endowment and low market price.

In China and India, because of their large area, energy transportation between production and consumption regions is important. Figure 3 and Figure 4 show the regional distribution of energy production in these two countries. These figures show that the distribution of resources varies so much.

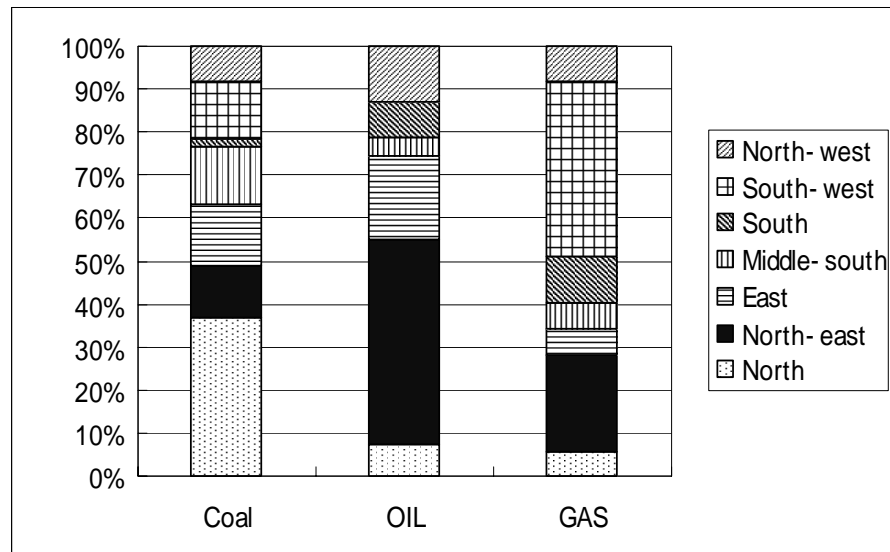


Figure 3 Share of energy production by region in China

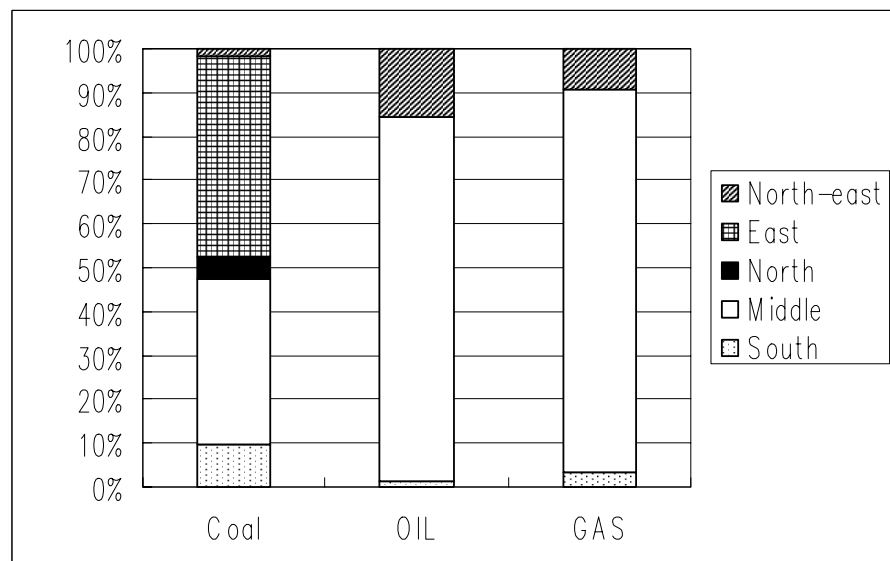


Figure 4 Share of energy production by region in India

Based on the above observation, one can conclude that the following three issues are significant in the future energy strategies: (1) to meet the future increasing energy demand, (2) to utilize the existing energy resources efficiently incorporating technology choices, and (3) to consider the environmental and the transporting issues.

2. Framework of the model

2.1 Classification of regions

This study aims at the assessments of energy technologies incorporating transportation

infrastructures to deal with the geographical distribution of fossil energy resource endowment and quality. We focus on the Asian area shown in Figure 5 disaggregating it into 15 subregions summarized in Table 1. We then develop a multiregional energy-economy model including domestic and international energy transportation to treat the geographic resource distribution explicitly. The contribution of desulfurization options is assessed in the model.

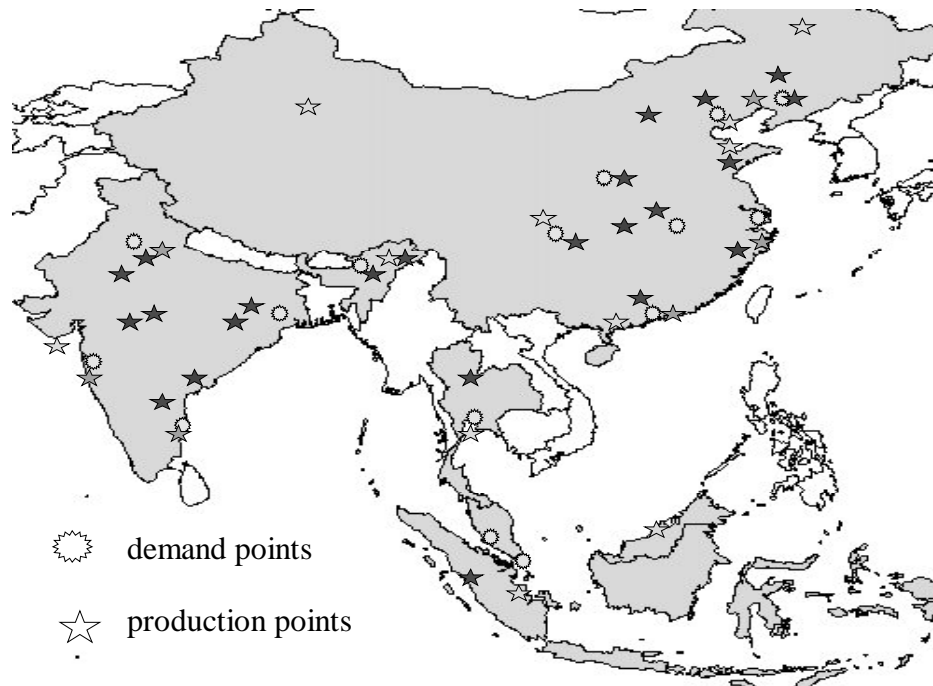


Figure 5 Asian Region and energy demand and production points of the model

Table 1 Energy demand subregions of the model

country	Demand subregions
China	Beijing Shengyang Shanghai Wuhan Guangzhou Chongqing Xian
India	Madras□Bombay□Delhi Calcutta□Gauhati
Thailand	Bangkok
Malaysia	Kuala Lumpur
Singapore	Singapore

We adopt Indonesia, Russia, Middle-East countries for the oil and the natural gas production countries. Indonesia, Australia and South Africa are assumed to be the coal supply countries for Asia.

2.2 Structure of the Model

The structure of the model is shown in Figure 6. Similar to the existing energy/economics model, this model incorporates production functions which consist of capital stock, labor and energy inputs by region. The output is distributed among investment, consumption and energy cost.

The energy supply block involves production, pre-treatment of coal, transportation and conversion. This model focuses on SO₂ and CO₂ as air pollutants caused by combustion process. SO₂ can be removed by desulfurization equipments.

The objective function is the maximization of discount sum of consumption similar to GLOBAL 2100 [Manne and Richels, 1992].

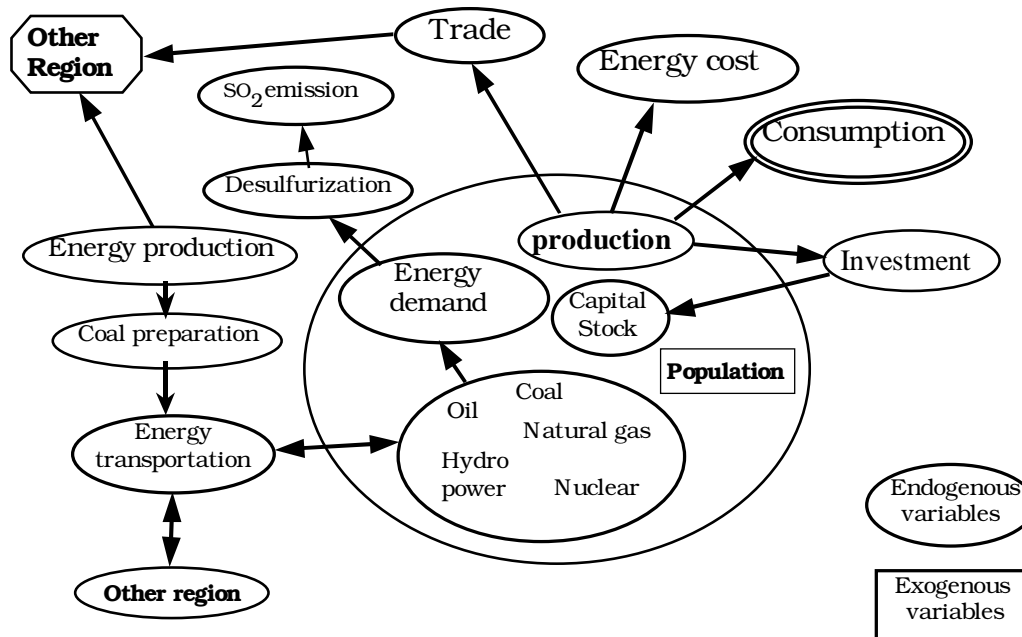


Figure 6 Structure of the model (one region)

2.3 Model formulations

The followings are the definition of indicators:

i: region (1:North China, 2:North-east China, 3:Middle China, 4:Middle-south China, 5:South China, 6:West-south China, 7:North-west China, 8:South India, 9:Middle India, 10:North India, 11:East India, 12:North-east India, 13:Thailand, 14:Malaysia, 15:Singhapole, 16:Indonesia, 17:Australlia, 18:South Africa, 19:Russia and 20:Middle-East)

kf: fossil fuels (1: coal, 2:oil and 3:natural gas)

kr: carbon free energy sources (1: hydraulic power, 2:nuclear power)

t: period

2.3.1 Energy resource endowment

The assumptions on energy resource endowments are shown in Table 2 [MITI, 1998]. Table 3 summarizes the initial resource extraction costs [Inagaki, Kikuchi, Fujii and Yamaji, 1996]. It is assumed that the extraction cost rises as cumulative production increases [Rogner, 1997].

Table 2 fossil energy resource endowment and potential hydraulic power and nuclear power supply

	Coal (million ton)	Oil (million ton)	Natural gas (million ton)	Hydropower (MTOE)	Nuclear power (MTOE)
North China	183296.0	472.6	174.9	3.0	0.0
North-east China	8878.4	1585.1	586.5	3.0	0.0
East China	18616.0	597.3	221.0	7.3	145.98
Middle-east China	9164.8	68.7	20.6	9.8	0.0
South China	1432.0	65.5	9.7	6.0	236.19
South-west China	30644.8	82.0	56.0	115.8	0.0
North-west China	34368.0	459.5	170.0	20.7	0.0
South India	13127.2	62.8	21.6	18.5	0.9
Middle India	48895.0	584.3	354.6	3.5	0.7
North India	1061.8	0.0	2.9	6.6	0.5
East India	142265.6	0.0	0.0	3.4	0.0
North-east India	889.7	147.9	113.7	19.6	0.0
Thailand	1422.0	51.6	171.2	0.7	0.0
Malaysia	0.0	588.0	1375.4	5.25	0.0
Singapore	0.0	0.0	0.0	0.0	0.0
Indonesia	6412.0	756.5	1302.3	---	---
Australia	23346.0	0.0	0.0	---	---
South Africa	24243.0	0.0	0.0	---	---
Russia	0.0	0.0	9996.9	---	---
Middle East	0.0	22546.7	8061.5	---	---

Table 3 Resource extraction costs in US dollars per ton

	Coal	Oil	Natural gas
China	39.29	55.78	95.20
India	26.91	55.78	85.40
Thailand	19.64	55.78	85.40
Malaysia	---	55.78	85.40
Indonesia	39.29	55.78	85.40
Australia	39.29	55.78	---
South Africa	39.29	55.78	---
Russia	---	55.78	77.00
Middle East	---	55.78	95.20

2.3.2 Energy production and demand

The relationships among energy production, energy export, import and supply are expressed by simplified linear equations:

$$FEP_{ikft} = \sum_{j=1}^{15} FEMex_{jykt} \quad (1)$$

$$REEP_{jkrt} = REEMex_{jkrt} \quad (2)$$

FEP_{ikft} : fossil energy production (million ton)

$FEMex_{ijkft}$: energy transportation from production area to demand area (million ton)

EXF_{ikft} : energy export to non Asian regions (million ton)

$REEP_{jkrt}$: electric power generation by nuclear and hydraulic power (MTOE)

$REEMex_{jkrt}$: electric power export from power generation area (MTOE)

2.3.3 Energy transportation and supply

The losses of energy transportation are one of the major key features for the assessment of energy strategies especially in China and India since there are some possible options. For instance, (1) crude coal transportation by railways (existing), (2) washed and cleaned coal transportation, (3) natural gas pipeline transportation, (4) electric power transportation by high voltage direct current transmission, (5) distributed energy supply systems, etc.

In our model, it is assumed that electric power generated by the nuclear and the hydraulic power is transported and that the energy losses by transportation are approximated by linear equations.

$$FEMin_{ijkft} = FEMex_{ijkft} - FEMIs_{ijkft} \quad (3)$$

$$FEMIs_{ijkft} = (RLS_{kf} \times RID_{ijkft} + WLS_{kf} \times WID_{ijkft} + PLS_{kf} \times PID_{ijkft}) \times FEMex_{ijkft} \quad (4)$$

$$FEI_{-}S_{jkft} = \sum_{i=1}^{20} FEMin_{ijkft} \times Hp_{ikft} \times U_{kf} \quad (5)$$

$$REI_{-}S_{jkrt} = REEMin_{jkrt} \quad (6)$$

$REEMin_{jkrt}$: electric power imports by carbon free resources (MTOE)

$FEMIs_{ijkft}$: energy consumption for the transportation of fossil fuels (MTOE)

RLS_{kf} □ rate of energy loss of railway transportation (%)

RID_{ijkft} □ distance of railway energy transportation □1000km□

WLS_{kf} □ rate of energy loss of ship transportation (%)

WID_{ijkft} □ distance of ship energy transportation □1000km□

PLS_{kf} □ rate of energy loss of gas pipeline transportation (%)

PID_{ijkft} □ distance of pipeline transportation

$FEI_{-}S_{jkft}$ □ total supply of fossil fuel (MTOE)

$FEMin_{ijkft}$ □ energy imports of fossil fuel from energy production area to demand area (million ton)

Hp_{ikft} □ energy output coefficient by produced region and by source □kcal/kg□

U_{kf} □ unit conversion factor

$RE1_{-}S_{jkrt}$ □ electric power supply by nuclear and hydraulic power (MTOE)

2.3.4 Energy demand

Figure 7 shows the skeleton of the energy supply-demand flow in the model. This model incorporates five primary energy sources, two secondary energy products and three final energy demand sectors. Energy demands for the transportation and the other sectors are given exogenously.

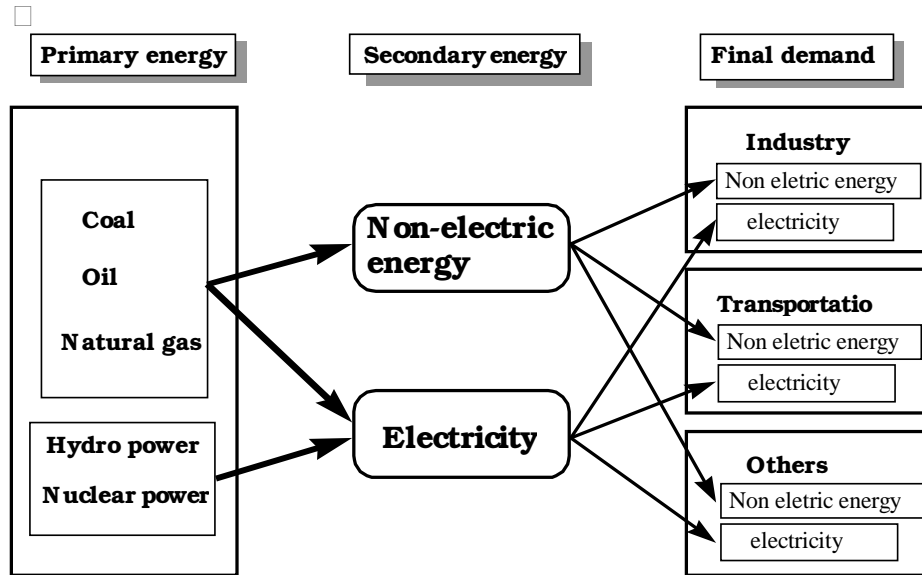


Figure 7 Energy flow structure

The equations are the followings:

$$FE_1_{-}S_{jkft} = FE_2_{-}NE_{jkft} + FE_2_{-}E_{jkft} \quad \square 7 \square$$

$$FE_2_{-}E_{jkft} = PP_{kft} \times FE_2_{-}E_{jkft} \quad \square 8 \square$$

$$EC_{-}NE_{jt} = \sum_{kf=1}^3 FE_2_{-}NE_{kft} \quad \square 9 \square$$

$$EC_{-}E_{jt} = \sum_{kf=1}^3 FE_2_{-}E_{kft} + \sum_{kr=1}^2 RE_1_{-}S_{jkrt} \quad (10)$$

$$\square \square \square \square \square \square \square \square \quad EC_{-}NE_{jt} = EC_{-}NEI_{jt} + EC_{-}NEP_{jt} + EC_{-}NET_{jt} \quad (11)$$

$$EC_{-}E_{jt} = EC_{-}EI_{jt} + EC_{-}EP_{jt} + EC_{-}ET_{jt} \quad (12)$$

$FE_2_{-}NE_{jkft}$: fossil fuel supply for non-electric energy (MTOE)

$FE_2_{-}E_{jkft}$ □ fossil fuel supply for electric power (MTOE)

$FE_2_{-}E_{jkft}$ □ electric power generation by fossil fuel (MTOE)

PP_{kft} □ energy efficiency of power generation (%)

$EC_{-}NE_{jt}$ □ total non-electric power demand (MTOE)

- EC_E_{jt} □ total electric power demand (MTOE)
 $RE_1_S_{jkrt}$ □ electric power supply by nuclear and hydro power (MTOE)
 EC_NEI_{jt} □ non-electric power demand of industry sector (MTOE)
 EC_NET_{jt} □ non-electric power demand of transportation sector (MTOE)
 EC_NEP_{jt} □ non-electric power demand of other sector (MTOE)
 EC_EI_{jt} □ electric power demand of industry sector (MTOE)
 EC_ET_{jt} □ electric power demand of transportation sector (MTOE)
 EC_EP_{jt} □ electric power demand of other sector (MTOE)

2.3.5 Energy transportation

We impose upper limit constraints on the energy transportation among regions. The transportation capacities are assumed to be expandable in response to the demand increase. Equations with respect to railways are shown in the below.

$$RC_{jt} \geq \sum_{i=1}^{20} \sum_{kf=1}^3 FEMex_{ijkft} \times RID_{ijkft} \quad (13)$$

$$WC_{jt} \geq \sum_{i=1}^{20} \sum_{kf=1}^3 FEMex_{ijkft} \times WID_{ijkft} \quad (14)$$

$$PC_{jt} \geq \sum_{i=1}^{20} \sum_{kf=1}^3 FEMex_{ijkft} \times PID_{ijkft} \quad (15)$$

$$RC_{jt+1} = \delta \times RC_{jt} + NRC_{jt} \quad (16)$$

- RC_{jt} □ transportation capacity of railway (ton km)
 WC_{jt} □ transportation capacity of ship (ton km)
 PC_{jt} □ transportation capacity of pipeline (ton km)
 δ □ depreciation rate per decade (%)
 NRC_{jt} □ additionally implemented transportation capacity of railway (ton km)

2.3.6 SO2 Emission

Emission of pollutants in a region is calculated by the total consumption of oil and coal multiplying the coefficients of sulfur and carbon contents. These values are extracted from the literature [NISTEP, 1991] as shown in Table 4.

Table 4 Contents of sulfur in weight percent

(%)	Coal	Oil
North China	0.58	0.40
North-east China	1.26	0.40
East China	1.62	0.40
Middle-south China	1.04	0.40

South China	1.04	0.40
South-west China	3.12	0.40
North-west China	1.76	0.40
South India	0.60	-
Middle India	0.60	0.50
North India	0.60	-
East India	0.64	-
North-east India	4.10	0.50
Thailand	2.40	0.50
Malaysia	-	0.50
Singapore	-	-
Indonesia	0.50	0.50
Australia	0.55	-
South Africa	0.50	-
Middle-East	-	3.00

$$SO_{jt} = \sum_{i=1}^{20} \sum_{kf=1}^3 FEM_{ikft} \times PSO_{ikf} \times Up_{kf} \quad (17)$$

$$S_{jt} = SO_{jt} - RSO_{jt} \quad (18)$$

SO_{jt} : atmospheric sulfur emission (metric ton)

PSO_{ikf} : sulfur contents (%)

Up_{kf} : emission coefficients

S_{jt} : sulfur emission by fuel burning (metric ton)

RSO_{jt} : removed sulfur by desulfurization equipments (metric ton)

We adopt two stage desulfurization processes: (1) coal preparation process (50% desulfurization, 25% energy loss and 40% weight reduction) and (2) simple desulfurization equipment in post-combustion process (80% desulfurization and 70% capacity utilization rate).

We also hypothetically impose constraints on the sulfur emission limits by sector.

$$S_{jt} \leq \overline{SO}_j \quad (19)$$

2.3.7 Economic activity block

Economic activity block aggregates regional industries into one sector similar to ETA-MACRO and GLOBAL 2100 [Manne, 1992] model. For the simplicity, Cobb-Douglas production function with four inputs, i.e. capital stock, labor, electric energy and non-electric energy, is employed for each region.

$$Y_{jt} = (1 + \mu_{jt}) A_j K_{jt}^\alpha L_{jt}^\beta NE_{jt}^\gamma EE_{jt}^{1-\alpha-\beta-\gamma} \quad (20)$$

$$C_{jt} = Y_{jt} - IS_{jt} - E_{jt} - Cost_{jt} \quad (21)$$

Y_{jt}	□ gross output	$A_j, \mu_t, \alpha, \beta, \gamma$	□ parameters
K_{jt}	□ capital stock	L_{jt}	□ labor input
EE_{jt}	□ electric power input		
NE_{jt}	□ non electric power input		
C_{jt}	□ consumption in region j		
IS_{jt}	□ investment for region j		
E_Cost_{jt}	□ energy cost of region j		

For China and India, consumption, consumption and net trade income are aggregated into national level.

$$TC_t(m) = \sum_{j=1}^{N(m)} C_{jt} + Fuel_EX(m)_t \quad (22)$$

m: suffix of nation

N(m): number of regions of nation m

$TC(m)_t$ □ national total consumption of m nation

$Fuel_EX(m)_t$ □ income of fuel energy export of m nation

Energy costs consists of extraction costs, power generation costs, liquidification costs for transportation sector, transportation costs, trade transaction costs and desulfurization costs. These parameters are extracted from the literature [NISTEP, 1991] [Inagaki, Kikuchi, Fujii and Yamaji, 1996].

$$E_Cost_{jt} = EPC_{jt} + EEC_{jt} + HC_{jt} + MC_{jt} + IMC_{jt} + RSC_{jt} \quad (23)$$

EPC_{jt} □ extraction cost

EEC_{jt} □ power generation cost

HC_{jt} □ liquidification cost

MC_{jt} □ transportation cost

IMC_{jt} □ net import cost

RSC_{jt} □ desulfurization cost

In this model, we adopt a simple objective function to represent the consumption maximization and equity distribution among regions. That is,

$$\max \sum_m \sum_{t=1}^T L(m)_t \ln(TC(m)_t / L(m)_t) \quad (24)$$

The parameters of production functions are estimated based on the literatures [World bank, 1997][Ezaki, 1999][China, 1999]. These are summarized in Table 5.

Table 5 Parameters of production functions

	A	α	β	γ	$1 - \alpha - \beta - \gamma$
North China	3.05927	0.44019	0.48720	0.03204	0.04057
North-east China	2.72534	0.51262	0.41683	0.02845	0.04210
East China	3.08931	0.48639	0.44518	0.01969	0.04874
Middle China	5.66465	0.19544	0.73779	0.02451	0.04226
South China	2.92704	0.49632	0.44032	0.02094	0.04242
South-west China	6.99616	0.01732	0.91372	0.02679	0.04217
North-west China	4.85964	0.16422	0.76877	0.02476	0.04225
South India	1.99709	0.67263	0.28292	0.02883	0.01562
Middle India	1.57530	0.72858	0.22021	0.02863	0.02258
North India	2.00289	0.62438	0.32981	0.02879	0.01702
East India	2.49888	0.50881	0.44686	0.02884	0.01549
North-west India	2.32319	0.58441	0.37102	0.02883	0.01574
Thailand	5.33968	0.45693	0.52449	0.01187	0.00671
Malaysia	4.86781	0.54082	0.42507	0.02251	0.01160
Singapore	3.47396	0.67707	0.31015	0.00951	0.00327

Table 6 shows the assumptions on power generation plants [Sugiyama, 1999].

Table 6 Power generation costs

	Construction cost (Million\$/Gw)	Capacity factor (%)	Annualization rate (%)	Life time (year)
Coal fired plant	1360	70	17	20
Oil fired plant	1260	70	17	20
Gas fired plant	1170	70	17	20
Hydraulicpower	2000	45	13	50
Nuclear power	2000	75	17	25

3. Simulations

3.1 Simulation scenarios

The model is simulated for four decade, 1995-2035. Our model consists of 19,000 variables and 16,000 constraints with nonlinear ones. The model runs on the GAMS software. One simulation takes around 30 hours on IBM compatible PC with Pentium III 700MHz.

In this paper, we compare following three simulation scenarios:

CASE-1: business as usual (BAU) case

CASE-2: Sulfur emission is controlled to be no more than that of 1995 value with desulfurization implementation.

CASE-3: Sulfur emission is controlled to be no more than that of 1995 value without desulfurization implementation.

Needless to say, CASE-3 seems not realistic. This case evaluates how fuel switch options can solely achieve sulfur emission control target.

3.2 Simulation results

Figure 8 – 10 show the total primary energy supply in Asia for the above three cases. It can be observed that coal and oil are still mainly used in all cases including CASE-3. The total primary energy supply in CASE-2 in 2035 is 3529 MTOE while that in CASE-1 (BAU) is 4040 MTOE. Even though natural gas supply increases from 515 MTOE in BAU to 562 MTOE in CASE-2, it is not enough to substitute coal widely used in this region. It should be noted that even in CASE-1 (BAU), natural gas demand increased 14.2 times from 1995 (6.86% annual growth rate). Due to the huge investment for the natural gas utilization infrastructure and the resource availability issues, expansion of natural gas use is restricted. To meet the increasing energy demand in Asia, coal still keeps its position. Thus, sulfur stabilization control policy involves energy saving options as well as the desulfurization equipments. Figure 10 exhibits the primary energy supply profile in CASE-3 where sulfur emission is stabilized at 1995 level by only “fuel switch” policy. Then primary energy supply decreases to 2151 MTOE in 2035 with 2.28% annual growth rate. Total amount of coal and oil consumption of CASE-3 in 2035 is no more than 40% of that of CASE-1, which may not be realistic.

Figure 11-16 exhibit the fossil fuel consumption of China and India by inland region in CASE-1. In CASE-1, BAU case, both coal and natural gas continuously increase while oil does not so much. SOX emission in Asia is shown in Figure 17. Sulfur emission rises rapidly as fossil fuel consumption grows.

Figure 18-23 show the fossil fuel consumption in CASE-2 where sulfur emission control is imposed not to exceeds its 1995 level by region and desulfurization equipment is available. One can observe that coal and natural gas consumptions are almost similar to those in CASE-1 while oil consumption saturates and is decreasing. In this sense, desulfurization option does not affect the fundamental energy supply pattern so much.

Those in CASE-3, sulfur emission control is attempted to achieve by only fuel switching, are shown in Figure 24-29. Natural gas consumption slightly increase in both China and India while oil consumptions are decreasing and the growth rates of coal are much lower than CASE-1. These figures suggest that in such strategy, fuel switch from coal to natural gas is not enough to regulate sulfur emission and reduction of energy consumption is needed.

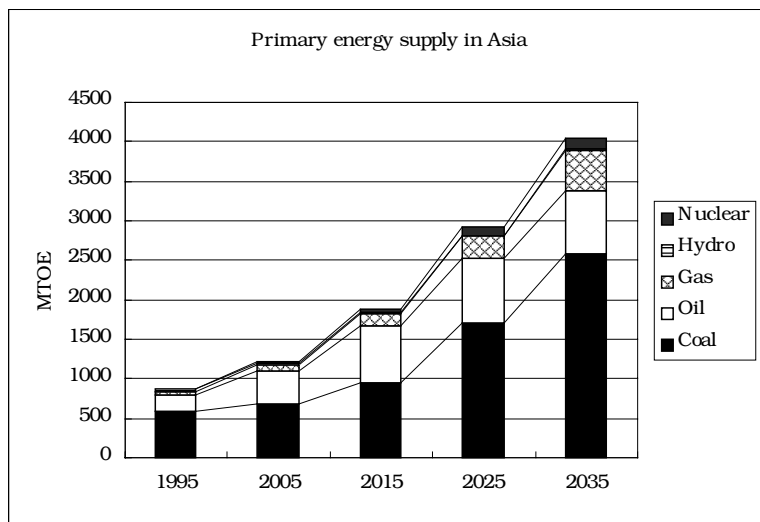


Figure 8 total primary energy supply profile of Asia in CASE-1 (BAU)

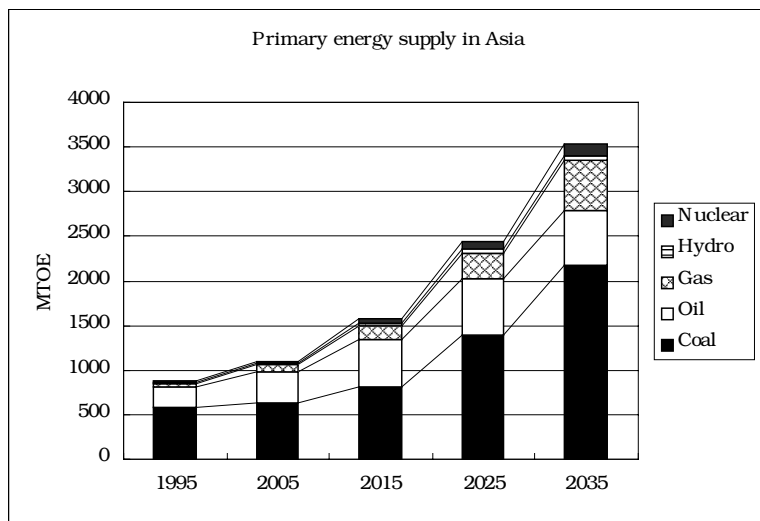


Figure 9 total primary energy supply profile of Asia in CASE-2

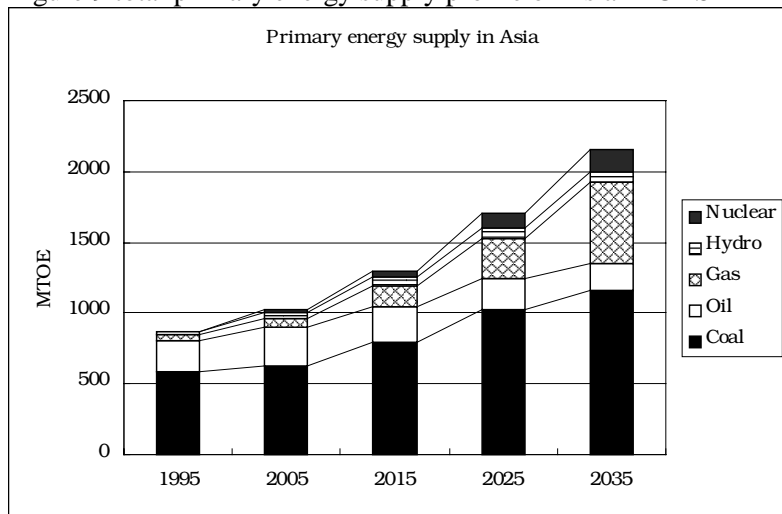


Figure 10 total primary energy supply profile of Asia in CASE-3

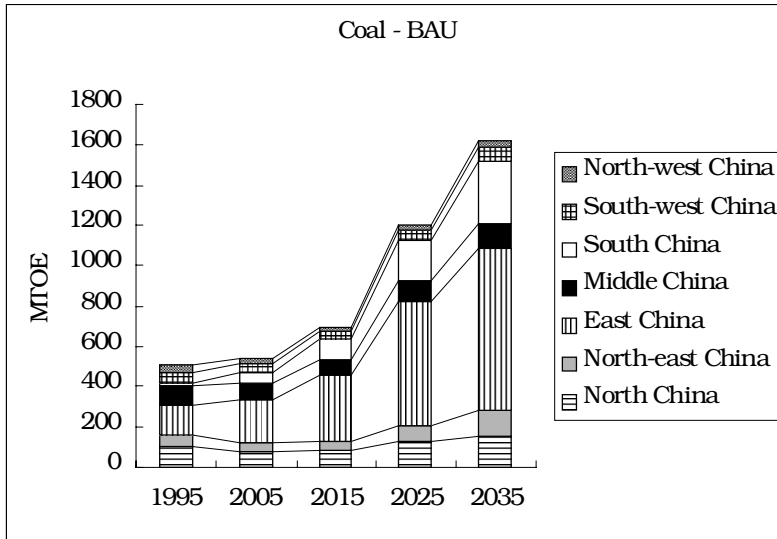


Figure 11 Coal demand of China in BAU (CASE-1) by region

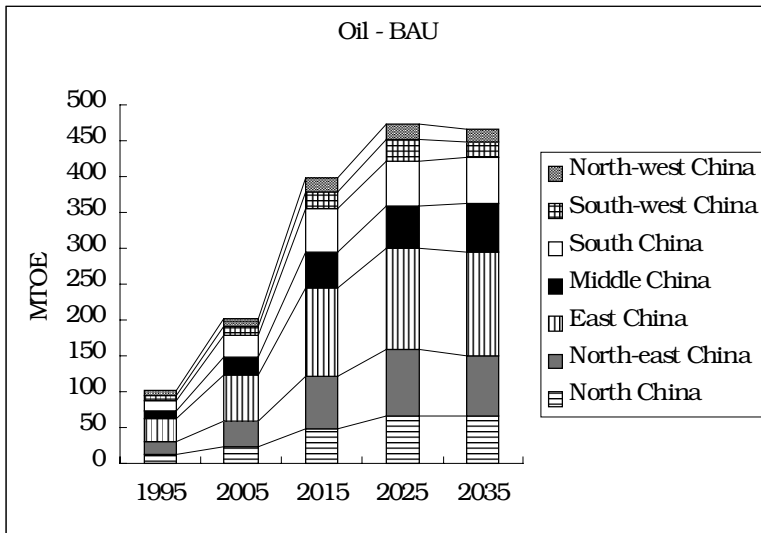


Figure 12 Oil demand of China in BAU (CASE-1) by region

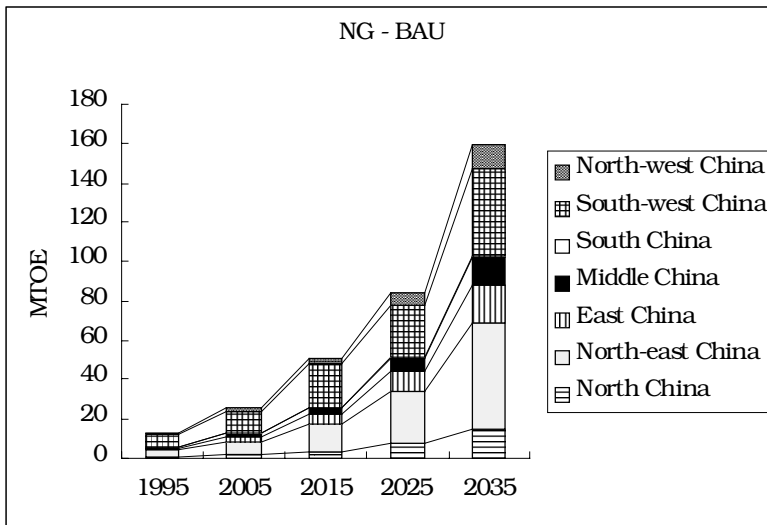


Figure 13 Natural gas demand of China in BAU (CASE-1) by region

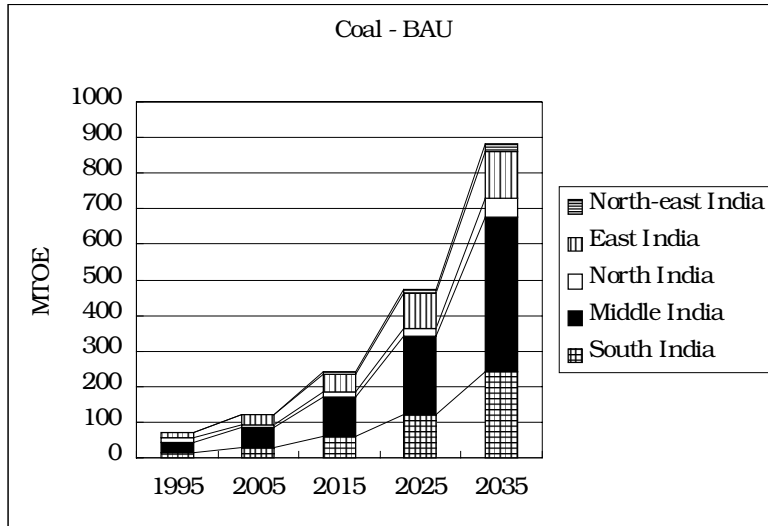


Figure 14 Coal demand of India in BAU (CASE-1) by region

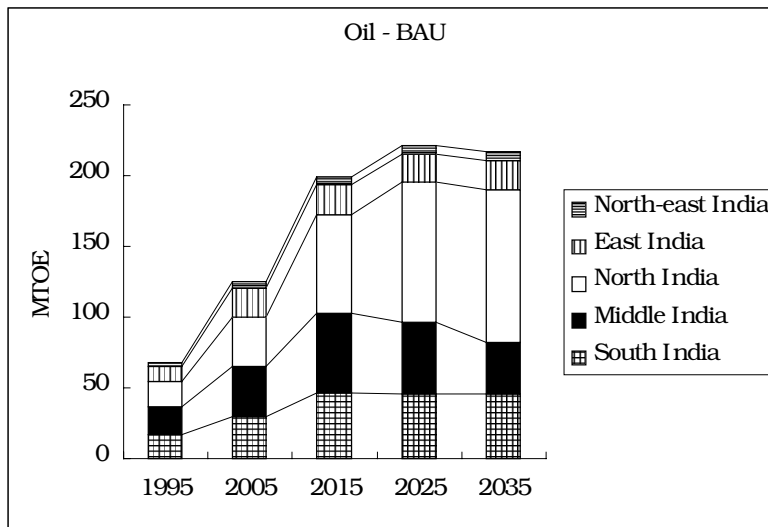


Figure 15 Oil demand of India in BAU (CASE-1) by region

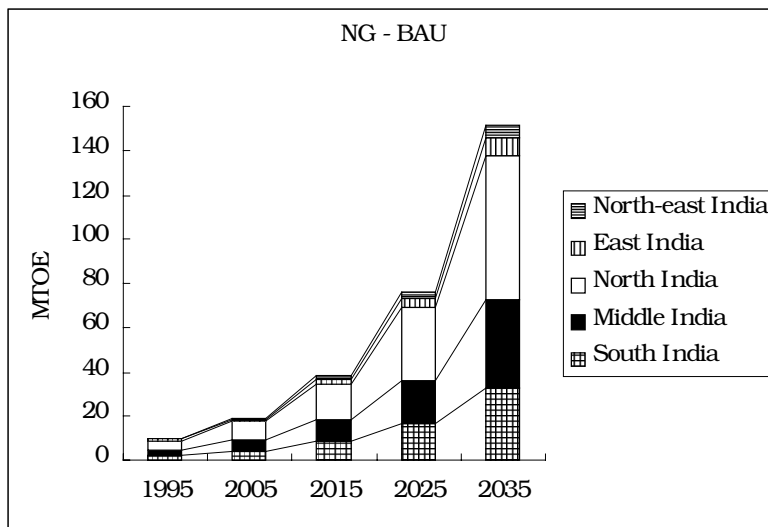


Figure 16 Natural gas demand of India in BAU (CASE-1) by region

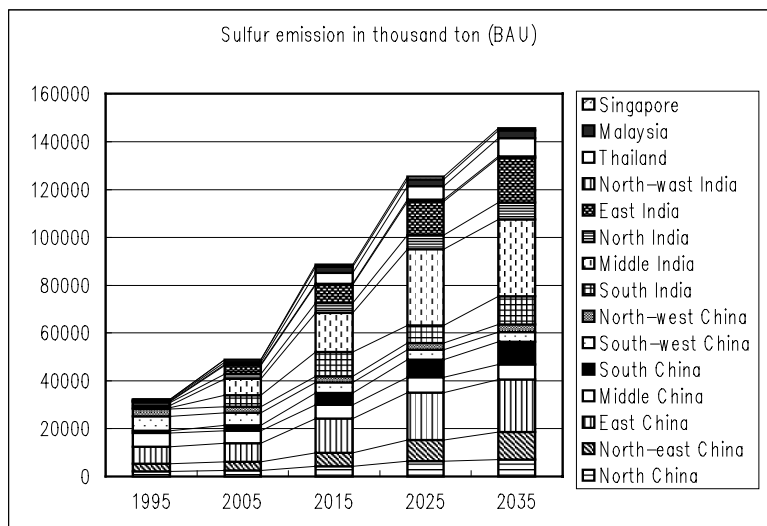


Figure 17 Sulfur emission in BAU

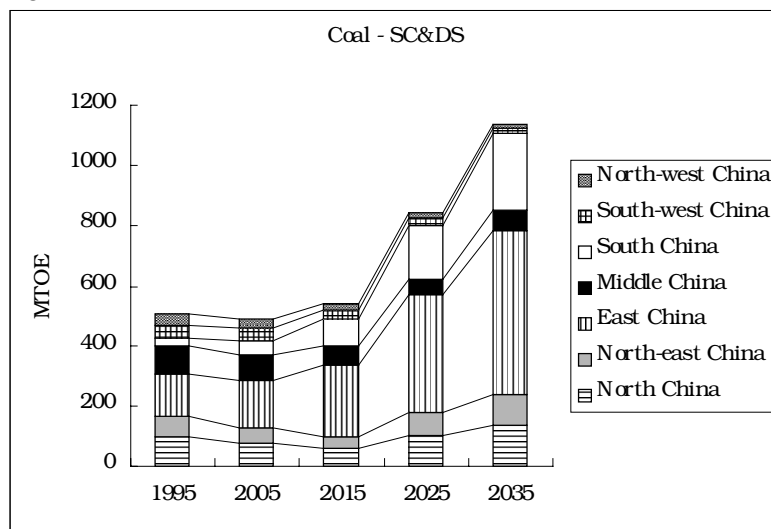


Figure 18 Coal demand of China in sulfur control and desulfurization (CASE-2) by region

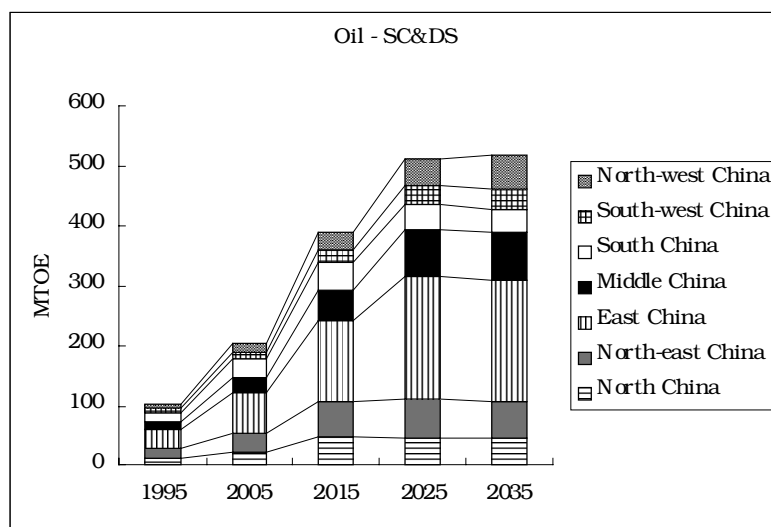


Figure 19 Oil demand of China in sulfur control and desulfurization (CASE-2) by region

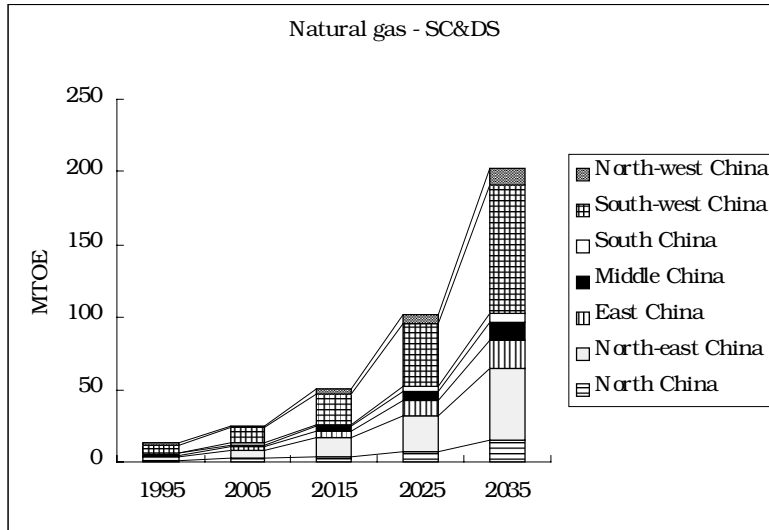


Figure 20 Natural gas demand of China in sulfur control and desulfurization (CASE-2) by region

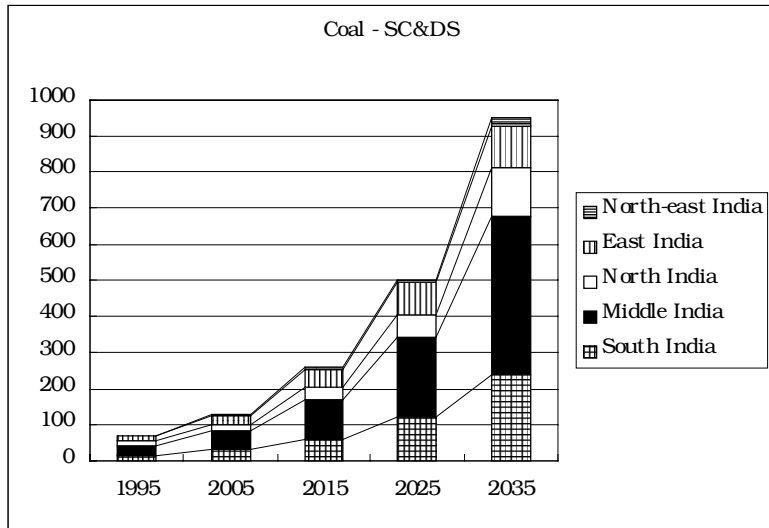


Figure 21 Coal demand of India in sulfur control and desulfurization (CASE-2) by region

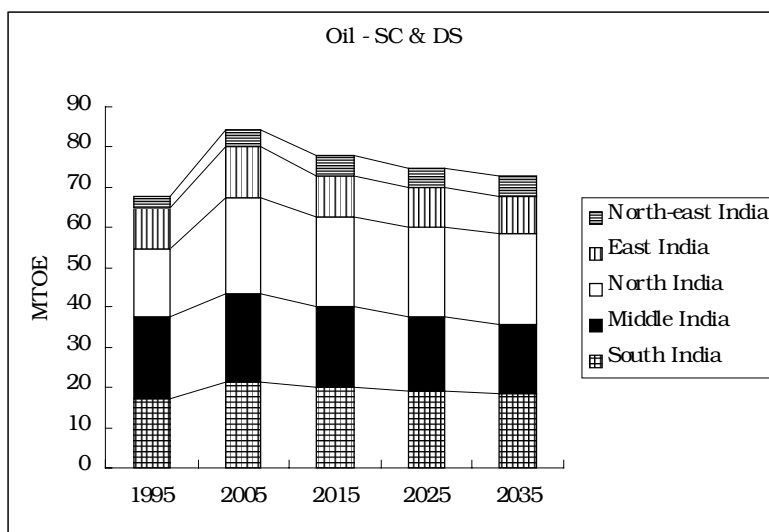


Figure 22 Oil demand of India in sulfur control and desulfurization (CASE-2) by region

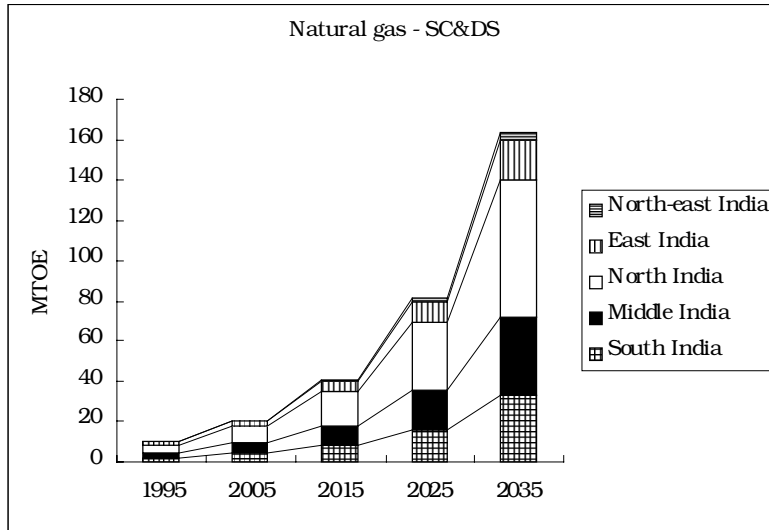


Figure 23 Natural gas demand of India in sulfur control and desulfurization (CASE-2) by region

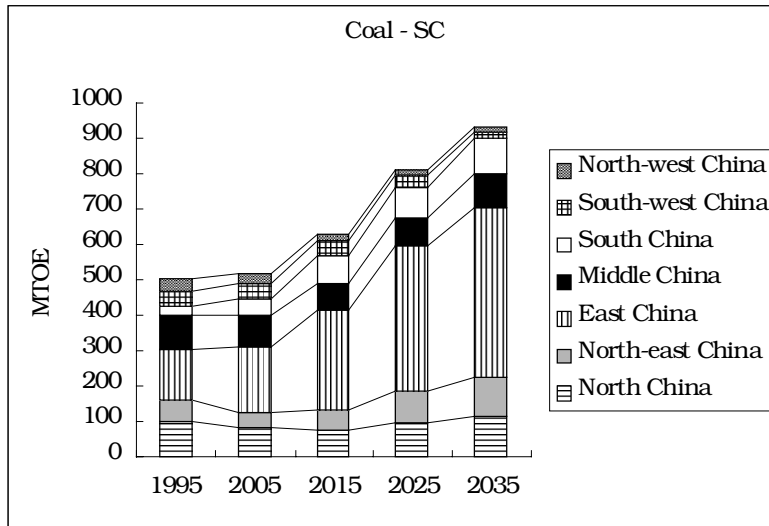


Figure 24 Coal demand of China in sulfur control without desulfurization (CASE-3) by region

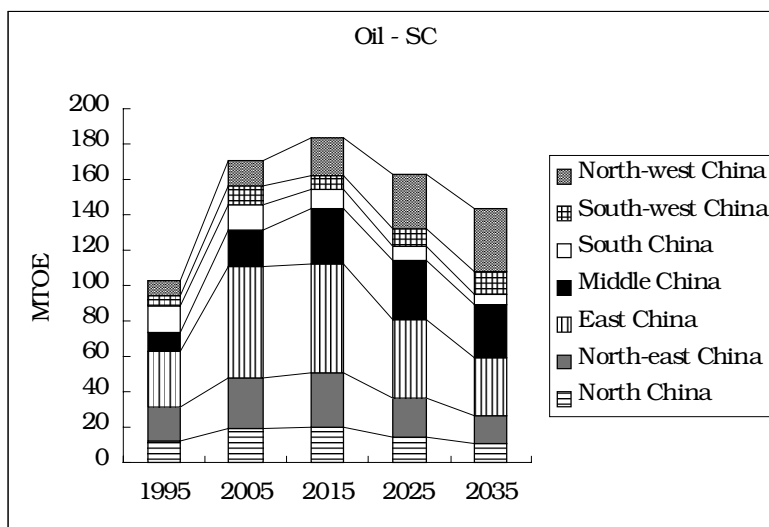


Figure 25 Oil demand of China in sulfur control without desulfurization (CASE-3) by region

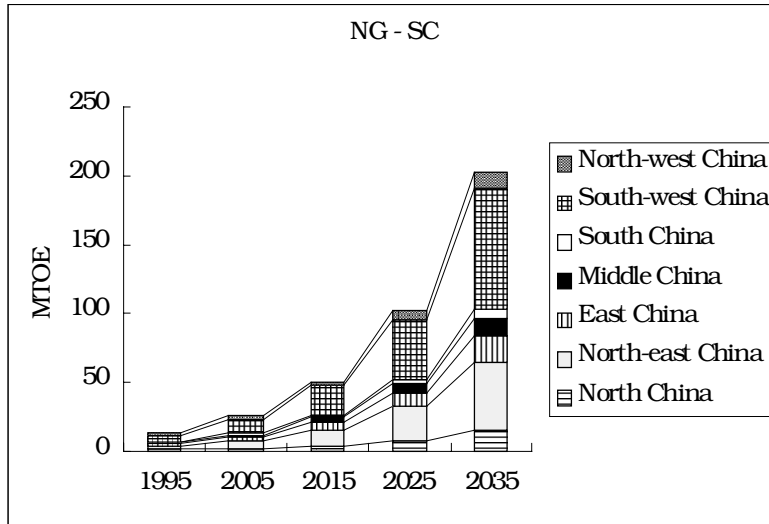


Figure 26 Natural gas demand of China in sulfur control without desulfurization (CASE-3) by region

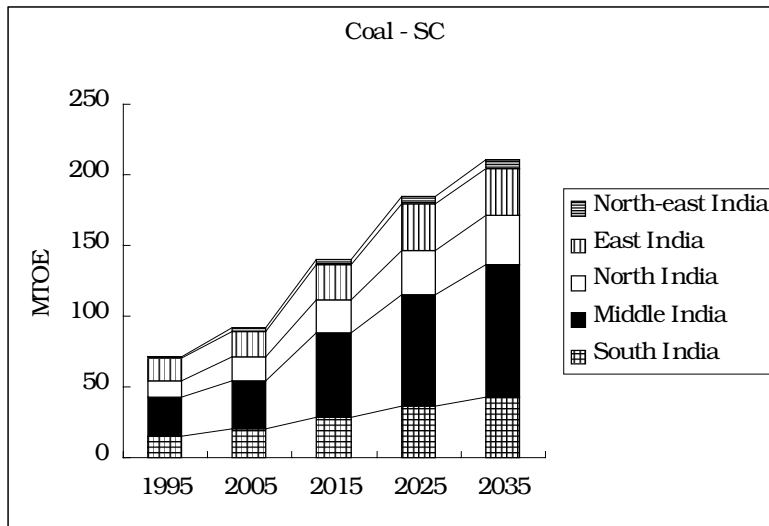


Figure 27 Coal demand of India in sulfur control without desulfurization (CASE-3) by region

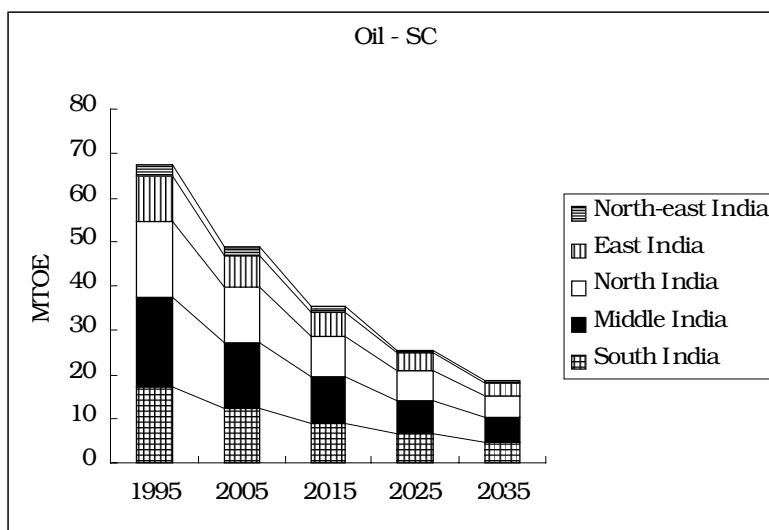


Figure 28 Oil demand of India in sulfur control without desulfurization (CASE-3) by region

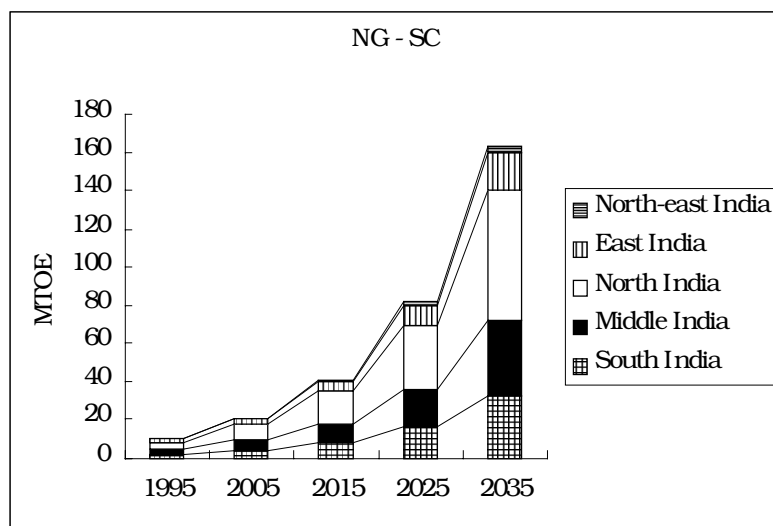


Figure 29 Natural gas demand of India in sulfur control without desulfurization (CASE-3) by region

In figure 28, total oil consumption in India decreases. It is slightly counter-intuitive. One reason is the low sulfur contents of Indian coal shown in Table 4. Both coal and oil should be reduced under the sulfur emission mitigation policy when no desulfurization equipments are implemented. If natural gas resources are abundant, it will be a main energy resource in the future. However, since its expansion is restricted by the technical and the financial reasons, energy conservation is the only option for India. These again suggest the needs for the clean coal options.

Figure 30 shows the GDP profiles of regions. Annual economic growth rates range between 3.23% (South-west China) and 7.02% (middle India). These are summarized in Table 7.

Figure 31 summarizes the loss of GDP among cases. The contribution of desulfurization appears clearly especially in Indian regions. This figure suggests that “fuel switch” towards natural gas expansion is not sufficient for the sulfur emission control and that “clean coal” options is still economically effective.

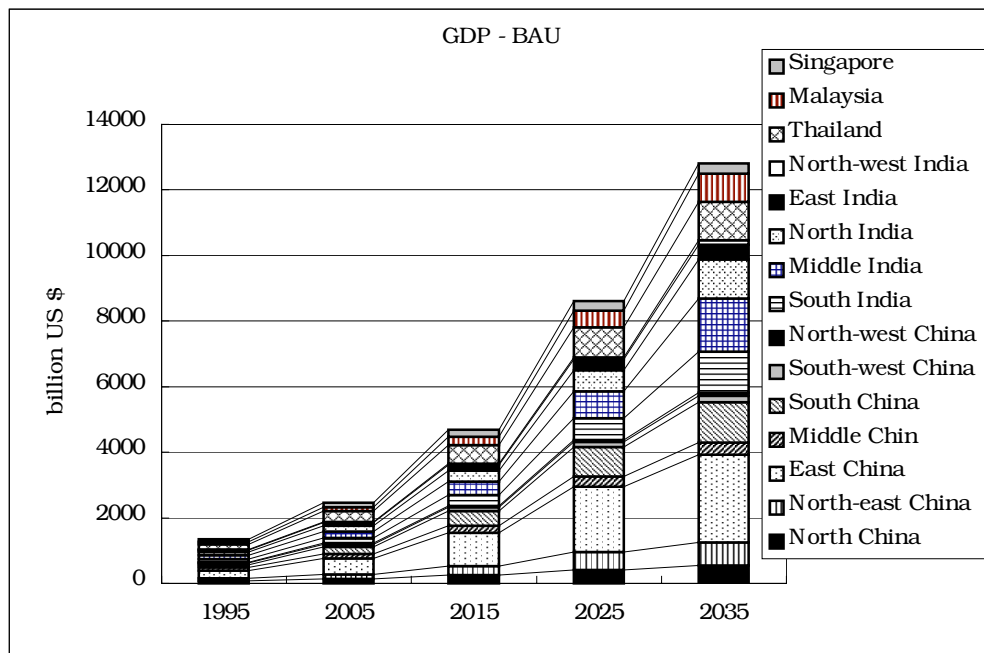


Figure 30 GDP profiles of BAU case (CASE-1)

Table 7 Annual economic growth rates for 1995 - 2035

North China	North-east China	East China	Middle Chin	South China
4.88%	5.96%	6.26%	3.48%	6.77%

South-west China	North-west China	South India	Middle India	North India
3.23%	3.28%	6.66%	7.02%	6.37%

East India	North-west India	Thailand	Malaysia	Singapore	Asia total
5.24%	6.19%	4.88%	6.24%	3.52%	5.77%

Figure 32-36 show the production of fossil fuels for Asia. Figure 32 show the case of coal for CASE 1 (BAU). North China and South-west China are the main sources for Asia. Australia and South Africa are also main suppliers for this region in spite of abundant coal resources within Asia. It is because of the higher loss of inland transportation than mariner transportation to the Asian main demand areas. Figure 33 shows the coal production of CASE-2. Although the total production for Asia is not so different from Figure 32, coal production from South-west China disappears. Since the sulfur content of coal in this region is high as is shown in Table 4, North China and Australia are the main sources with desulfurization systems. Table 34 shows the case of sulfur control without desulfurization, where total coal consumption decreased significantly and coal from Australia and South Africa dominates the Asian market because of the superiority of sulfur content.

Figure 35 exhibits the oil production profile for Asian market. The market share of Middle-East grows very rapidly and comes to 54% in 2005 and 89% in 2015.

Similar situation is observed in the case of natural gas supply. In Figure 36, more than half of natural gas demand in Asian region is supplied by Russia and Middle-EAST in 2035 although natural gas production in Asia covers most of the gas market in this region until 2015. These phenomenon

may not change assuming the continuous economic growth unless large enough gas resources are discovered and proved.

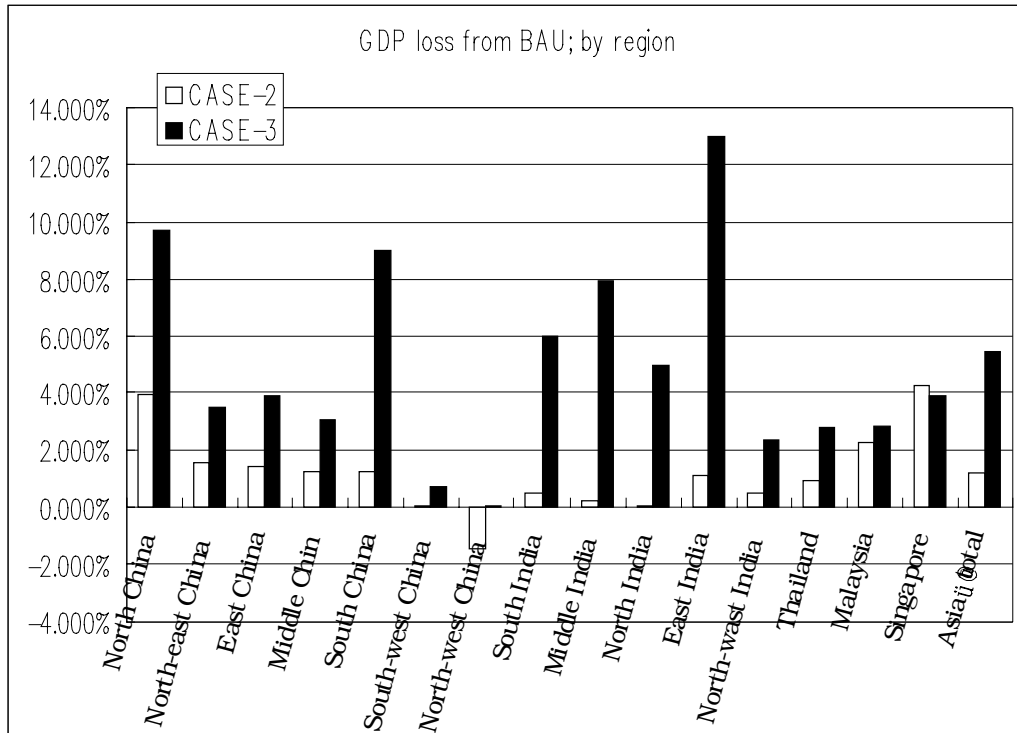


Figure 31 GDP losses in 2035 by region

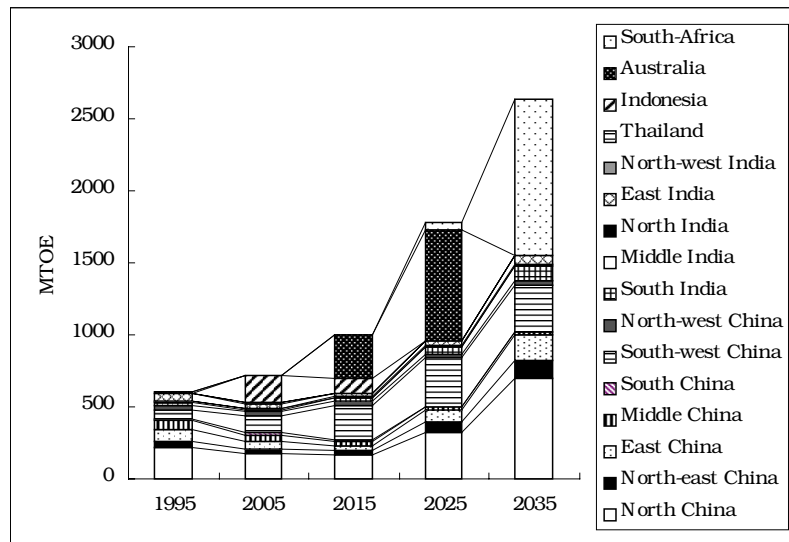


Figure 32 Coal production for Asian region in CASE-1 (BAU)

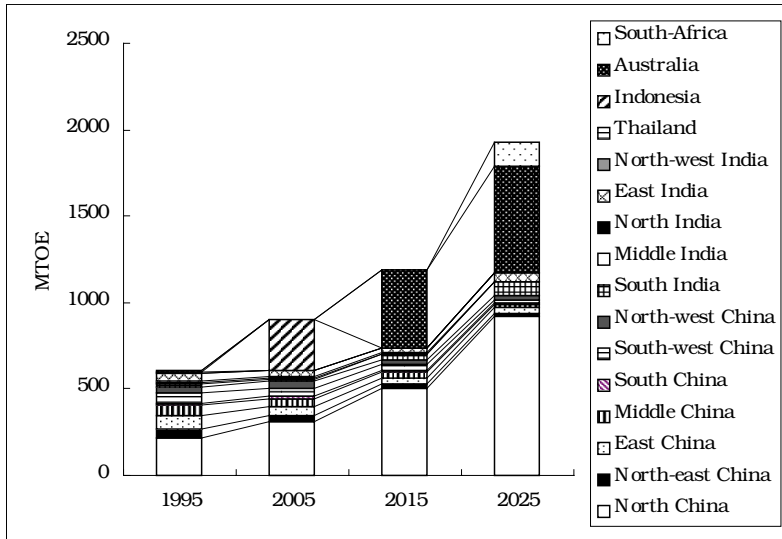


Figure 33 Coal production for Asian market in CASE-2 ;sulfur control with desulfurization

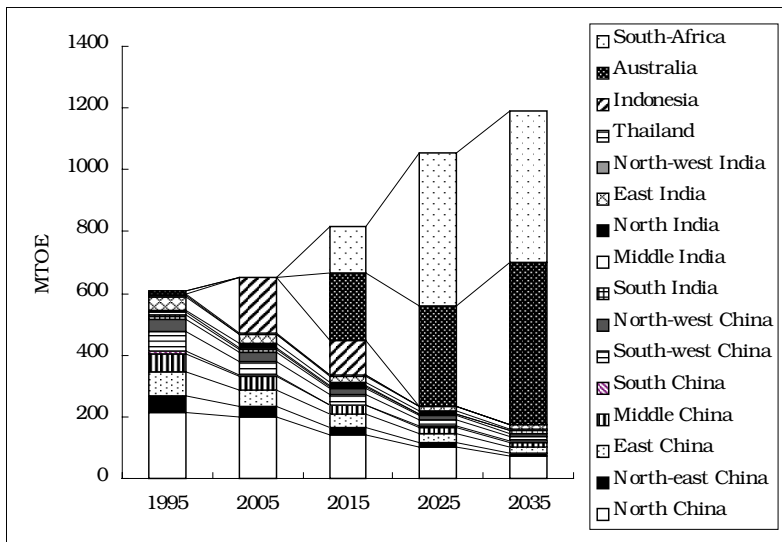


Figure 34 Coal production for Asian market in CASE-3; sulfur control without desulfurization

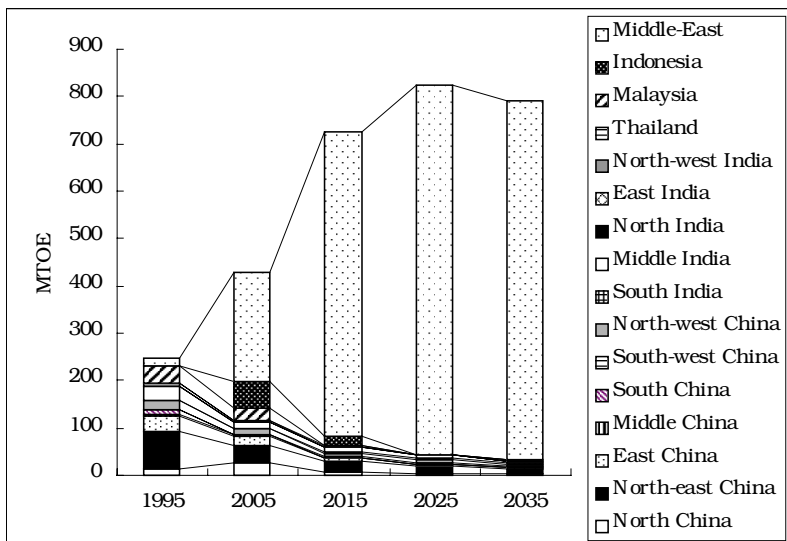


Figure 35 Oil production for Asian market in CASE-1 (BAU)

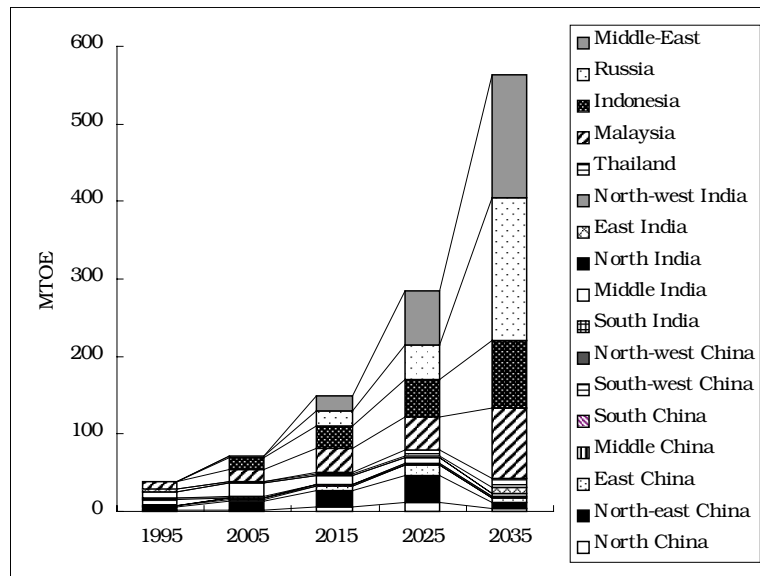


Figure 36 Natural gas production for Asian market in CASE-1 (BAU)

4. Conclusion

In this paper, we developed a model for the assessment of energy and environmental technologies for Asian regions taking into account the geographical distribution of resource endowments and the variety of quality. Since the dynamics of economies in this region is so active and uncertain, it may be too early to conclude the middle term energy strategies. There are so many remaining issues other than the above in our research. For instance, the technology options for the energy intensive industries are not dealt with explicitly. “Clean coal” technologies other than desulfurization including coal liquidification and gasification for integrated gas combined cycle (IGCC) and fuel cells (IGFC) should be taken into account so long as coal is still used for major energy sources and environmental control policies are implemented. Greenhouse gas emission control policies should also be assessed involving local environmental pollution mitigation measures.

Nonetheless, our study provides some significant findings on the energy strategies:

- (1) Coal will still be a major role in primary energy supply portfolio even in the sulfur control case. The cost of desulfurization equipments is much lower than the “fuel switch” to gas options since the supply of natural gas will not meet the energy demand and environmental measures due to the geographical resource distribution and constraints on the technical and the financial issues against the expansion of infrastructure for gas use
- (2) Clean coal technologies will significantly mitigate the cost for the sulfur emission control policies under the increasing energy demand.
- (3) Coal production within Asian regions will not be enough to cover the demand because of not the resource endowment but the transportation reasons.
- (4) Asian regions will have to depend on such non Asian countries as Australia, Russia and South Africa with respect to fossil fuel imports. This finding suggests the importance of the establishment of mariner fuel transportation infrastructures as well as the gas pipelines across the continent.

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