# RAINS-ASIA:
# AN ASSESSMENT MODEL FOR AIR POLLUTION IN ASIA

## Chapter 4

## Emissions and Control

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# 4. EMISSIONS AND CONTROL

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## Abbreviations used

### Fuel types

| | |
|---|---|
| BC1 | Brown coal/lignite, high grade |
| BC2 | Brown coal/lignite, low grade |
| HC1 | Hard coal, high quality |
| HC2 | Hard coal, medium quality |
| HC3 | Hard coal, low quality |
| DC | Derived coal (coke, briquettes) |
| OS1 | Other solids, low sulfur (biomass, waste, wood) |
| OS2 | Other solids, high sulfur (incl. high S waste) |
| HF | Heavy fuel oil |
| MD | Medium distillates (diesel, light fuel oil) |
| LF | Light fractions (gasoline, kerosine, naphtas, LPG) |
| GAS | Gas |

### Sectors

| | |
|---|---|
| CON | Fuel production and conversion |
| PP | Power plants, district heating |
| DOM | Households and other consumers |
| TRA | Transport |
| IN_BO | Combustion in boilers for electricity and heat |
| IN_OC | Other industrial combustion (furnaces) |

## 4. EMISSIONS AND CONTROL

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### *4.1 Introduction*

Developing an accurate and detailed picture of sulfur dioxide emissions in Asia is a crucial component of the RAINS-ASIA project and serves multiple purposes. It is an output of the characterization of the energy and industrial situation that links the economic development of the region with the damage it causes to the environment. By studying the use of fossil fuels for provision of energy services and production levels in industrial manufacturing, it is possible to estimate the releases of sulfur dioxide to the atmosphere. These emissions then serve to drive the atmospheric transport, transformation, and deposition model, which calculates the temporal and spatial fate of the emissions. Subsequently, the impacts module estimates the vulnerability of ecosystems to these patterns of deposition. Also, by projecting future changes in energy and industrial development, future emissions can be estimated and future threats to the environment assessed.

The picture of current emissions from different types of facilities serves as a reference point for estimating the potential for reducing emissions. Figure 4.1 shows the flow diagram for the RESGEN/RAINS-ASIA model which highlights the ENEM (ENergy, Emissions and Control Module) components. The goal of the ENEM module is the development of regional and LPS emission scenarios for all 95 regions and 355 LPS included in the RAINS-ASIA model and the estimation of the incremental costs of pollution control associated with scenarios that reduce emissions. The emissions vectors produced by ENEM are available for input to the DEP (Atmospheric Transport and DEPosition) module, described in Chapter 5, to calculate the geographic distribution of acid deposition. By transforming the patterns of reduced emissions through the atmospheric deposition and impacts modules, a view of the consequent reduced environmental damage can be obtained in physical terms. If these physical measures could be converted to economic benefits, a full picture of the costs and benefits of different emission control options would be obtained.

The inputs to the ENEM model consist of a series of databases including:

- Regional and LPS energy consumption scenarios provided by the RESGEN model,
- Regional and LPS fuel characteristics databases (e.g., sulfur content, heating value and sulfur retention in ash) provided by the Asian Energy Network,
- Control technology and costs databases, and
- Model-user assumptions formulated into various "Control Strategies" which are developed by combining sector-, fuel-, and technology-specific control policy options for each region and LPS.

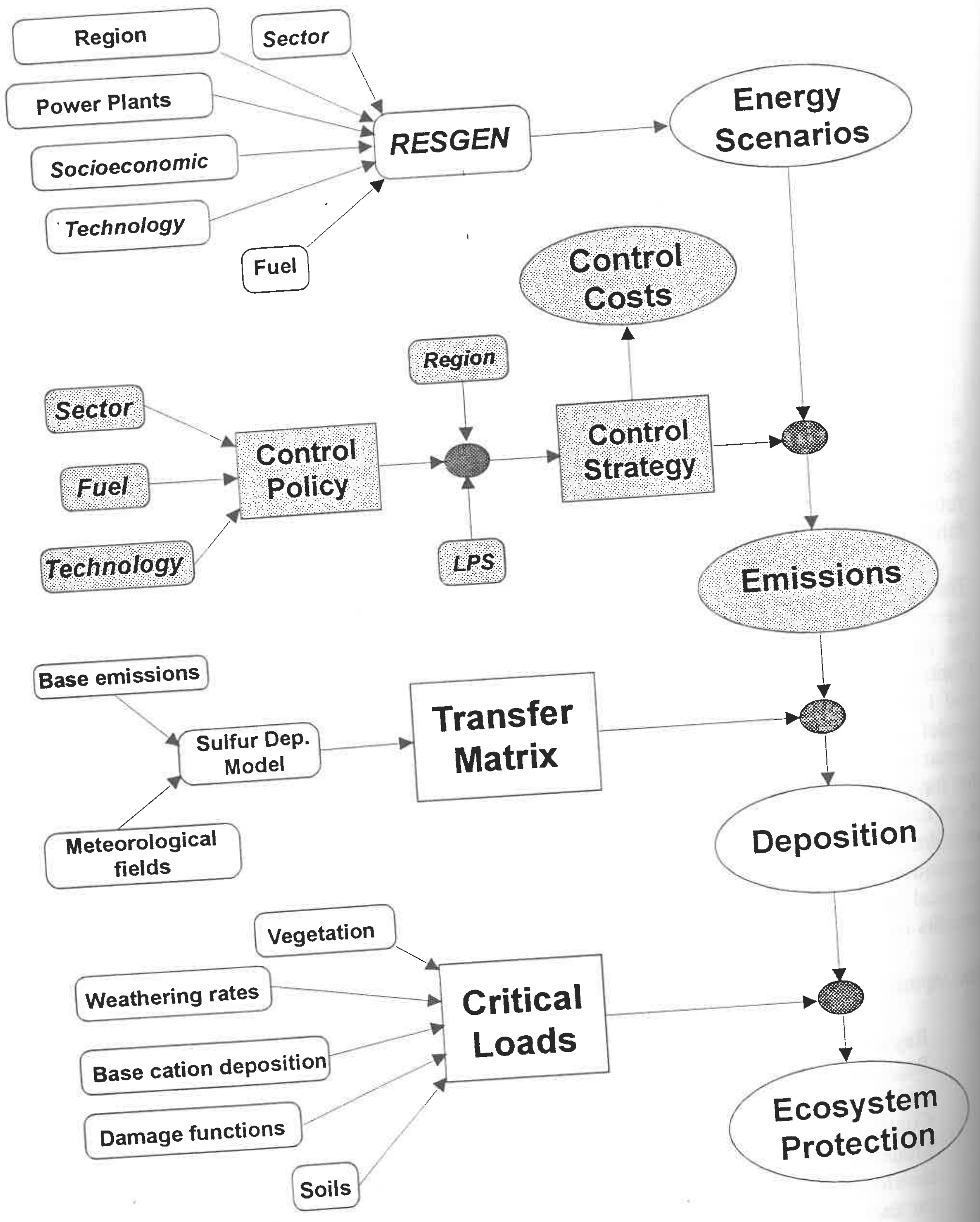

Figure 4.1 RESGEN/RAINS-ASIA flow diagram

Two distinct emission inventories were developed as part of the RAINS-ASIA project. Early in the project, a gridded 1° x 1° emissions inventory for the year 1987-1988 was compiled. The function of this inventory was primarily for the purpose of developing the atmospheric source/receptor relationship (see Chapter 5). This gridded inventory was used in certain specific studies and as a check on the more detailed base-year regional and LPS emissions inventory for 1990 developed later in the project.

The base-year regional and LPS emissions inventory was developed from databases constructed as part of the ADB-funded project. Detailed databases of energy use, industrial activity, and fuel characteristics for 95 regions were compiled by the network of Asian collaborators for the year 1990 (see Chapter 3). A thorough review of major point sources was also developed as part of this activity. Data for this phase of the project were collected in Asia and were developed, for the most part, independently from data gathered to construct the 1987-88 gridded emissions inventory.

As described in Chapter 3, the 1990 energy database was then used by the RESGEN model to develop future regional and LPS energy scenarios through the year 2020. These energy scenarios, including the base-year data for 1990, were combined with the regional fuel characteristics database in the ENEM module to calculate emissions scenarios for each energy scenario. The results were consistent regional and LPS emissions inventories for the base year, 1990, and three future years, 2000, 2010, 2020, for each energy scenario. Finally, a review of control technology conducted by IIASA and included in the ENEM module was used to compute alternative emission reduction scenarios and their associated costs. Each of these activities is reviewed in the sub-sections that follow.

### 4.2 *The gridded emissions inventory (1987-88)*

The gridded emissions inventory represents a snapshot in time of sulfur dioxide emissions in Asia in the late 1980's. It was prepared during the first year of the RAINS-ASIA project from the most recent data available. It was revised and extended during the second year of the project. The period of the data used in the inventory is best described as 1987-1988, reflecting minor differences in the years of the many data sources that were used to compile the inventory.

The inventory was originally compiled on a 1° x 1° grid for the entire Asian region and subsequently aggregated to 95 regions (reference Table 3.1) for use in developing the atmospheric transfer matrix and for evaluating the 1990 regional and LPS emissions inventory. All anthropogenic sources of emissions were included in the gridded inventory including both land-based emissions and emissions from international shipping. In contrast to some other inventories, sulfur dioxide emissions from the burning of agricultural wastes, dried animal wastes, and fuel wood were specifically included for many of the countries. Steady-state (non-eruptive) emissions from volcanoes were added towards the end of the project.

The gridded inventory is a combination of two main data sources. For Southeast Asia (10 countries) and the Indian subcontinent (6 countries), emissions were calculated specifically for this project using the methodology described below. Mongolia was added in the second year of the project also using this methodology. For the remaining six countries of East Asia

(China, Hong Kong, Japan, North Korea, South Korea, and Taiwan), the emission estimates of Akimoto and Narita (1994) were used.

For Southeast Asia, the Indian subcontinent, and Mongolia, information was initially compiled for major individual emission sources in the region. Fossil-fuel-fired power plants and industrial process sources that emit sulfur dioxide (e.g., copper smelters) were included. In all, 248 individual emission sources were included for these 17 countries, 94 of them being power generation facilities. Each individual emission source was assigned to its appropriate $1^{\circ} \times 1^{\circ}$ grid cell. The contribution of these sources to total energy use and industrial production was then subtracted from national totals. The remaining energy use and industrial activity was then converted to sulfur dioxide emissions using standard emission factors and shared out to grid cells according to the methodology described below. A national summary of the emissions contained in the inventory is presented in Section 4.2.2.

### 4.2.1 Methodology and assumptions

The following procedures were used to develop emissions for Southeast Asia, the Indian subcontinent, and Mongolia. Emissions were estimated for three major categories: (1) emissions from energy consumption, (2) emissions resulting from industrial processes, and (3) emissions from international shipping. Emission estimates for the countries of East Asia (China, Hong Kong, Japan, North Korea, South Korea, and Taiwan) were taken from Akimoto and Narita (1994).

**Emissions from energy consumption sectors**

Emissions were initially calculated at the national level from energy/fuel consumption data for the following sectors: industrial, power generation, and other energy consumption. Energy use by fuel type and sector was obtained from IEA (1989). Emission factors for coal and oil were derived from data on the heating value of fuels, the sulfur content, and the sulfur retention in ash. For coal, the sulfur content and sulfur retention in ash was obtained from Spiro *et al.* (1992), supplemented by many other sources of information on sulfur contents of coals produced in Asia. The sulfur content of different types of oil products is difficult to obtain with any reliability. Refinery products are generally not reported by sulfur content, which is known to vary widely across product streams, especially for heavier refined products. For this work, oil consumption estimates from IEA 1989 were divided into four categories: light refined products for transportation uses (0.03%S), kerosene (0.3%S), middle distillates primarily for diesel generators (0.4%S), and residual fuel oil for industrial and power generating units. Sulfur contents for this latter category varied between 2.5%S and 3.5%S, depending on knowledge of practices in specific countries.

For the power generation sector, data were gathered on the location and fuel consumption at specific generating facilities. The size and location of coal-fired power generating facilities was obtained from IEA Coal Research (1990). Locations and types of oil-burning power generation facilities were obtained primarily from three sources: U.N. (1989), IAEA (1988), and IAEA (1991). Emissions calculated for these individual emission sources were assigned to their specific grid cells and were subtracted from the national emission total for power generation. Once all power generation emission sources had been identified and

located, the remaining non-point source emissions were allocated to grid cells on the basis of population shares.

All other energy/fuel based emissions from the industrial sector and other energy consumption were treated as non-point source emissions. Non-point-source emissions were allocated to grid cells on the basis of population shares.

Biomass is an important fuel contributing to significant $SO_2$ emissions in many Asian countries. As such, it received special attention in this analysis. Biomass burning is a complex category for the Indian subcontinent because of the combined usage of animal wastes with fuel wood and agricultural waste. The approach used for countries in this region is described in Table 4.1. Emission factors used were: fuel wood, 0.6 kg $SO_2$/tonne fuel for residential cooking and 0.23 kg $SO_2$/tonne for residential heating; 6.0 kg $SO_2$/tonne fuel for animal wastes; and 0.52 kg $SO_2$/tonne for agricultural wastes (Smith, 1988). Table 4.2 lists the quantities of biofuels consumed. For the other countries of Southeast Asia, it was assumed that fuel wood and some agricultural wastes were the predominant fuel types; animal waste consumption was insignificant. Quantities of biofuels consumed in these countries were taken from World Resources (1992), and emission factors were taken from Spiro, et al. (1992).

Table 4.1 Assumptions for biomass emissions calculations for the Indian subcontinent

| Country | Assumptions/Sources Used |
|---|---|
| Bangladesh | Assume that energy derived from biomass is distributed evenly among fuel wood, animal dung, and agricultural wastes. Total biomass energy production obtained from ADB (1991). Emission factor (E.F.) for $SO_2$ emissions from agricultural wastes same as E.F. for fuel wood. Assume most of biomass used in residential stoves. |
| India | Emission factor for $SO_2$ emissions from agricultural wastes same as E.F. for fuel wood. Assume most of biomass used in residential sector. Biomass consumption values obtained from Joshi (1991) and WEC (1989). |
| Sri Lanka | Assume that agricultural wastes and animal dung use each same (by weight) as that of fuel wood. Fuel wood consumption value obtained from WEC (1989). Assume most of biomass used in residential stoves. Emission factor for animal dung, agricultural waste, and fuel wood same as in other countries. |
| Nepal | Assume that agricultural wastes and animal dung use are each equal (by weight) to 1/4 that of fuel wood use. Fuel wood consumption figure obtained from WEC (1989). Emission factor for $SO_2$ emissions from agricultural wastes same as E.F. for fuel wood. Assume most of biomass used in residential stoves. |
| Bhutan | Assume no significant use of agricultural wastes and dung. Fuel wood consumption obtained from WEC (1989). Assume most of fuel wood used in residential stoves. |
| Pakistan | Assume that agricultural wastes and animal dung use are (by weight) each 1/8 that of fuel wood use. Fuel wood consumption values obtained from WEC (1989). Assume that equal amounts of fuel wood used in residential stoves and residential heating. Emission factor for $SO_2$ emissions from agricultural wastes same as E.F. for fuel wood. |

Table 4.2 Biofuels consumption in the Indian subcontinent (1987-88)

| **Country** | **Fuel Consumed [$10^6$ tonnes/yr]** | | |
|---|---|---|---|
| | **Fuel Wood** | **Animal Wastes** | **Agricultural Wastes** |
| Bangladesh | 44.37 | 44.37 | 44.37 |
| Bhutan | 2.10 | - | - |
| India | 164.39 | 126.46 | 83.79 |
| Nepal | 11.37 | 2.84 | 2.84 |
| Pakistan | 14.64 | 1.83 | 3.66 |
| Sri Lanka | 5.81 | 5.81 | 5.81 |

**Emissions from industrial processes**

The locations of industrial manufacturing facilities and production quantities by facility were taken from the 1989 Minerals Yearbook. Emission factors used for each process that emits sulfur dioxide are described below. For the metals and cement industries, it was assumed that no add-on pollution control devices were in place. For petroleum refining, steel production, and pulp and paper production, equivalence to 1980s U.S. practice was assumed. Almost all of the industrial plants were precisely located according to the maps provided in the Minerals Yearbook.

Emission factors used for industrial process emissions were of two types. When the process is simple and emissions derive basically from a single activity, process-specific emission factors were used. These were taken either from Spiro, et.al. (1992) or U.S. EPA (1987a). These emission factors are considered quite reliable, although some variation is to be expected depending on quality of the raw materials processed.

| | |
|---|---|
| Primary copper smelting | 1060 tonnes $SO_2$ per 1000 tons of Cu produced |
| Primary lead smelting | 149 tonnes $SO_2$ per 1000 tons of Pb produced |
| Primary zinc smelting | 490 tonnes $SO_2$ per 1000 tons of Zn produced |
| Aluminum smelting | 20 tonnes $SO_2$ per 1000 tonnes of Al produced |
| Cement production | 5.1 tonnes $SO_2$ per 1000 tonnes cement produced |

For the more complex industrial processes, which have several sources of sulfur dioxide within the plant and considerable variation in process conditions and material inputs, process-specific emission factors are not recommended, especially for the development of regional or national inventories. In this case, emission factors were developed assuming equivalence to mid-1980s U.S. experience. The emission factors were developed by dividing U.S. industrial production figures by U.S. national process emissions published by the U.S. EPA (1987b). These latter estimates were built up from facility-level data for the U.S. and therefore embody a certain variety of facility and process types. It is implicitly assumed that facilities in the U.S. and Asia in the 1980s were somewhat similar. For the multinational industries such as petroleum refining, this is probably a reasonable assumption; however, in general we might expect emission factors developed in this way to be low. Pending a plant-specific survey of Asian facilities, however, this approach cannot be improved upon. Thus, the following emission factors were based on U.S. industry equivalence:

Petroleum refining: 48 tonnes $SO_2$ per 1000 bbd refining capacity
Steel production: 3.2 tonnes $SO_2$ per 1000 tonnes of steel produced
Pulp and paper production: 2.2 tonnes $SO_2$ per 1000 tonnes of pulp produced

### Emissions from international shipping

An analysis was performed to quantify the emissions of sulfur dioxide from shipping in Asian waters. No estimates for this source category had previously been developed. These emissions estimates are subject to some uncertainty, however, because of the absence of detailed data in international publications on shipping routes and volumes, as well as a lack of data on the sulfur content of fuels burned.

The region covered by this analysis extends from the Indian Ocean eastward to the southern coast of Japan. The sources of shipping emissions have been divided into two categories: international shipping and major ports. The former category is further subdivided into two types of trade: crude oil and dry bulk cargo (primarily grain, coal, and iron ore). These four commodities together account for about 75% of seaborne trade worldwide (United Nations, 1984). The major international shipping routes of crude oil and dry bulk cargo and traded volumes are illustrated in Figures 4.2 and 4.3 taken from Fearnley's World Bulk Trades 1988. Note that direct shipments from Australia to Japan via the Pacific Ocean are not included in this analysis, as they are not considered relevant to the acidic deposition problem in continental Asia.

For the purpose of calculating emissions, crude oil is assumed to be carried by typical VLCC 200,000 dwt tankers consuming 120 tonnes of oil per day, while traveling at 15 knots. Dry bulk commodities are assumed to be carried by typical Panamax bulk carriers carrying 70,000 dwt and consuming 55 tonnes of oil per day while traveling at 15 knots (Stopford, 1988).

The sulfur content of bunker oil burned in shipping fleets in the 1980s varied considerably (up to 5%S), averaging between 2.5 and 3.5%S (Acid News, 1989; CONCAWE, 1993). This analysis assumes the use of 3%S oil, on average. The CONCAWE report assumed an average sulfur content of 3.3% for bunker oils manufactured currently in European refineries. All sulfur in the oil is assumed to be released as sulfur dioxide. Emissions of sulfur dioxide were calculated on an annual basis for each $1^{\circ} \times 1^{\circ}$ grid cell corresponding to the particular routes and commodity volumes. Routes within grid cells were approximated to either diagonal, horizontal, or vertical transects. Emissions in each grid cell were summed for each of the six routes, to produce aggregated emissions for all international shipping. These emissions were represented as a separate region in the RAINS-ASIA model inventory.

Traffic within major ports is known primarily in terms of total tonnage of cargo handled,

with little information available on the distribution of types of commodities, types of ships, or sizes of ships. Clearly, traffic handled in these ports is a combination of local and foreign vessels transporting imported and exported goods and international vessels in transit. For the purposes of this analysis, only those ports handling more than 50 million tons of cargo in 1988 were included. This consisted of 12 ports, six of them in Japan. Table 4.3 lists these ports and the volumes of cargo handled (ISEL, 1992). All other ports -- including, for example, Indian ports, Indonesian ports, Port Kelang in Malaysia, Manila, and Bangkok -- handle significantly lower volumes of cargo. It is estimated that these twelve ports comprise 80% of all port traffic in the region.

For the purpose of calculating in-port emissions, both local and foreign cargo vessels were considered to represent total cargo traffic in the port. It was assumed that the typical vessel carries 70,000 dwt of cargo, averaging 11 knots and 18 tonnes of oil consumption per day, and travels in the port vicinity for 6 hours. This resulted in the emissions estimates shown in Table 4.3. Total port emissions are estimated to be approximately 10,000 tonnes of sulfur dioxide per year. These estimates may be low, but there is no information available on relative fuel consumption by vessel size and cargo volume in port conditions. It is unlikely that port emissions estimates could be improved without access to local information.

### 4.2.2 National emissions totals

Table 4.4 lists anthropogenic emissions of sulfur dioxide by country, together with emissions from international shipping that comprise the gridded base-year inventory. Total annual emissions for the period 1987-1988 are estimated to be 31.6 million tonnes, of which China alone is estimated to contribute 19.9 million tonnes, or 63%. India contributes 5.1 million tonnes (16%). The deposition patterns that result from this distributed array of sulfur dioxide emissions is discussed in Chapter 5.

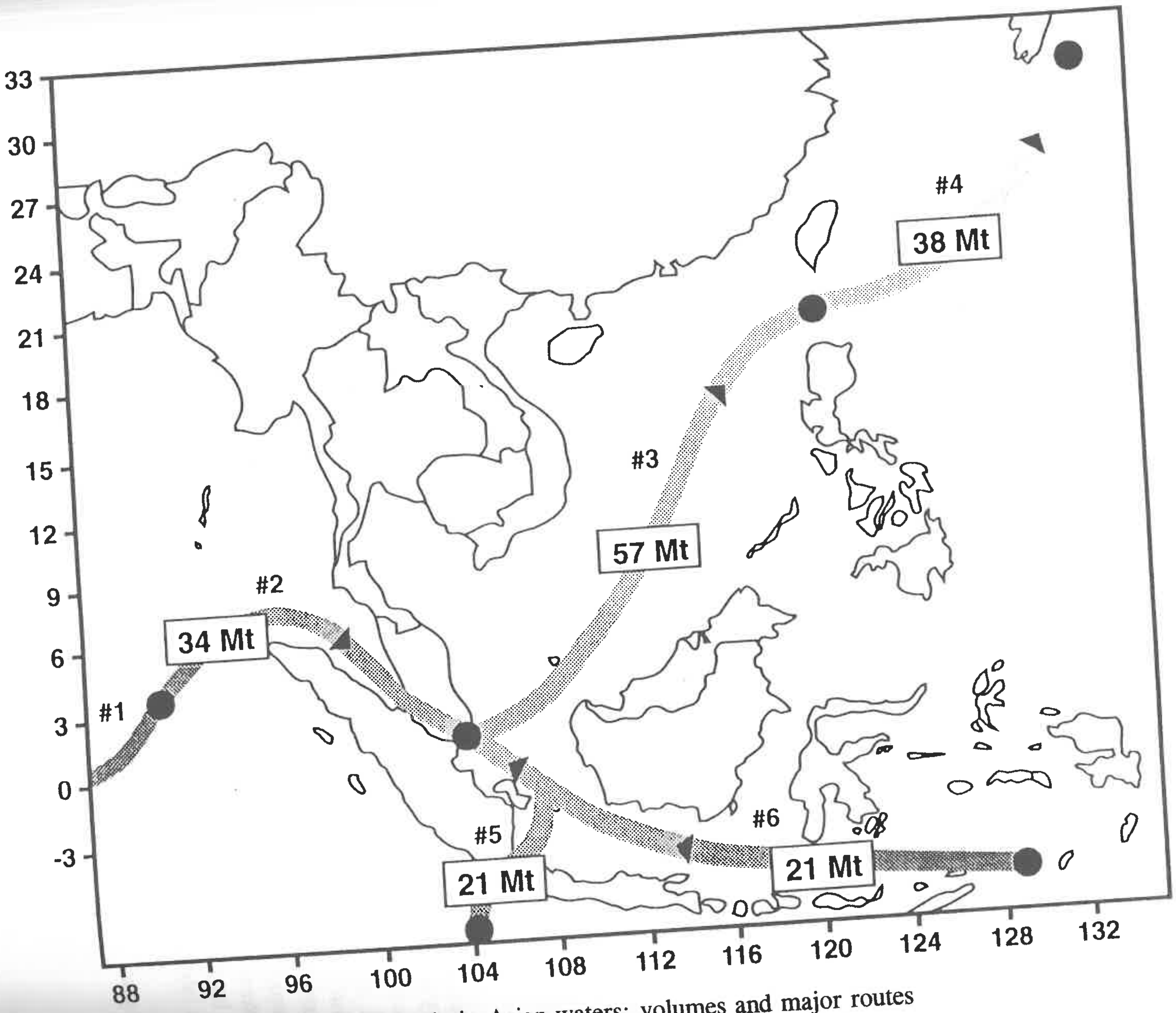

Figure 4.2 Crude oil seaborne trade in Asian waters: volumes and major routes

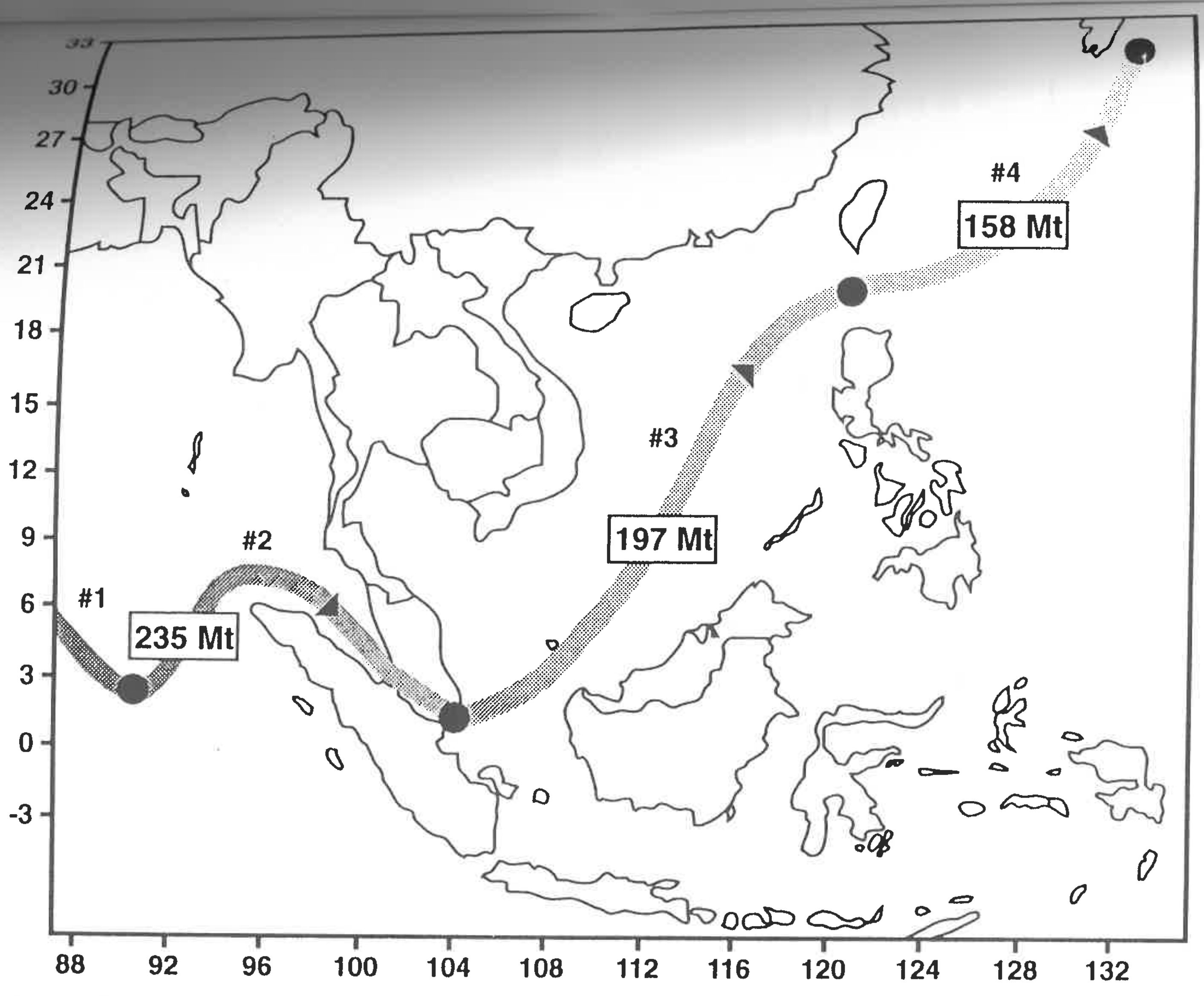

Figure 4.3 Dry bulk cargo seaborne trade in Asian waters: volumes and major routes

Table 4.3 Sulfur dioxide emissions from port traffic in Asia in 1988

| Country | Emissions | Country | Emissions |
|---|---|---|---|
| Bangladesh | 366,600 | Malaysia | 173,800 |
| Bhutan | 2,000 | Mongolia | 80,400 |
| Brunei | 600 | Myanmar | 14,600 |
| Cambodia | 2,800 | Nepal | 89,200 |
| China | 19,866,200 | Pakistan | 448,800 |
| Hong Kong | 133,400 | Philippines | 507,000 |
| India | 5,104,800 | Singapore | 169,600 |
| Indonesia | 396,100 | Sri Lanka | 89,100 |
| Japan | 977,900 | Taiwan | 545,200 |
| Korea, North | 407,000 | Thailand | 608,300 |
| Korea, South | 1,296,200 | Vietnam | 130,100 |
| Laos | 2,700 | [Shipping] | 225,600 |
| | | Total | 31,638,000 |

Table 4.4 Summary of anthropogenic sulfur dioxide emissions in 1987/1988 [tonnes/yr]

| Shipping Route | Emissions from Crude Oil Shipments | Emissions from Dry Bulk Shipments | Emissions from Oil and Bulk Shipments |
|---|---|---|---|
| 1 Persian Gulf to Indian Ocean | 62,100 | neg. | 62,100 |
| 2 Indian Ocean to Singapore | 47,700 | 7,900 | 55,600 |
| 3 Singapore to Taiwan | 44,500 | 14,500 | 59,000 |
| 4 Taiwan to Japan | 31,500 | 8,700 | 40,200 |
| 5 Australia to Singapore (from S) | 0 | 2,400 | 2,400 |
| 6 Australia to Singapore (from SE) | 0 | 6,300 | 6,300 |
| Totals | 185,800 | 39,800 | 225,600 |

## 4.3 *Current and future emissions in ENEM*

Emissions of sulfur dioxide are calculated by the ENEM module of RAINS-ASIA for a base-year, 1990, and three future years, 2000, 2010, and 2020. For these years, RAINS-ASIA calculates area source emissions for 95 regions and point source emissions for 355 LPS. Area source emissions are calculated for three major end-use energy sectors (domestic, transportation, and industry), two energy conversion sectors (power plants and other energy conversion), and industrial processes. Emissions from LPS are calculated for both energy conversion facilities such as power plants, and large industrial facilities. Emissions from area sources and LPS are calculated for each fuel type and sector combination. Emissions estimates may be displayed at many different levels of aggregation (i.e., regional, country, and Asia-wide; as area sources, LPS, and combined total; by sector; and by fuel).

### 4.3.1 Methodology, data, and assumptions

**Sectoral definitions**

Energy consumption and emissions data in ENEM are aggregated into 5 major sectors. These sectors are shown in Table 4.5. The sectors displayed in ENEM differ slightly from those used in the RESGEN model and described in Chapter 3. For the most part, the sectors in ENEM are either aggregations of several of the RESGEN sectors, or they represent sub-sectoral divisions of specific sectors. The choice of sectors for the ENEM module was driven by the need to make the sectors consistent with international databases and to provide the flexibility to include additional pollutants, such as $NO_x$, in future phases of model development.

Table 4.5 Energy and emission sectors in the ENEM module

| **ENEM Energy/Emission Sector** | **Description** |
|---|---|
| Domestic (DOM) | The domestic sector in ENEM is an aggregation of three sectors in RESGEN; residential, agricultural and commercial. |
| Industry (IN) | ENEM disaggregates the industrial sector into two subsectors: industrial energy consumption in boilers (BO), and other energy consumption (OC). Since RESGEN only calculates data for one industrial sector, all data are recorded in ENEM as industrial other energy consumption (IN-OC). |
| Transportation (TRA) | Energy consumption in the transportation sector. |
| Power Plants (PP) | Energy consumption in the power plant sector. |
| Other Conversion (CON) | Energy consumption in other energy conversion processes (i.e., oil refining, etc.). |

**Emissions estimates**

Regional area source emissions resulting from the direct combustion of fossil fuels are estimated from regional data and projections of fuel consumption, fuel characteristics, and applied emission control technologies by the following equations.

$$SO2_{i,j}(t) = \sum_{k}\sum_{l}\sum_{m} E_{i,j,k,l,m}(t) \times EF_{i,j,k,l} \times (1 - ec_{i,j,k,l,m})$$

where:

$$EF_{i,j,k,l} = 2 \times \frac{sc_{i,j,k,l}}{hv_{i,j,k,l}} \times (1 - sr_{i,j,k,l})$$

and:

$SO_2$ ⇒ Sulfur emissions [kt $SO_2$]
E ⇒ Energy consumption [PJ]
EF ⇒ Uncontrolled emission factor [kt $SO_2$/PJ]
sc ⇒ Sulfur content [fraction]
hv ⇒ Heating value of fuel [PJ/ton]
sr ⇒ Fraction of fuel sulfur retained in ash after combustion

ec ⇉ Fraction of emissions removed by pollution control
I ⇉ Country
j ⇉ Region
k ⇉ Fuel type
l ⇉ Energy consuming sector
m ⇉ Abatement technology

A detailed database of regional fuel consumption by economic sector for the base year (1990) was developed for each of the 95 regions in the model. Future regional fuel consumption by sector is provided as output from the RESGEN model. These energy data are described in detail in Chapter 3.

In addition to detailed base-year energy data, the project developed detailed data on fuel characteristics necessary to calculate regional area source emissions of $SO_2$. Data were collected for all 95 regions and included the sulfur content and heating value of all fuels, and the fraction of sulfur retained in the ash after combustion for only solid fuels. An iterative process was employed for quality control which included considerable feedback among the institutions in the entire Asian Energy Network responsible for data collection.

In the event that data on regional fuel characteristics could not be found, national averages were used. In one instance, data were completely unavailable at the country level for the fraction of sulfur retained in the ash following combustion of solid fuels. In this case, data from the RAINS-Europe model, representing "typical" values for these parameters in Europe, were used until more suitable Asian-specific data can be developed.

Examples of fuel characteristics data for the five energy consumption sectors are provided in tables 4.6 through 4.9. These data are for the Jiangsu (JINU) region of China (CHIN). Similar data are available for display for all 95 regions in the RAINS-ASIA model and may be displayed using the features of the ENEM module. Fuel characteristics are considered to be temporal constants in the model and are not available for modification by the user.

Table 4.6 Sulfur content by fuel and sector [%]

| Fuel* | Conversion | Power Plants | Domestic | Transport | Industry - Boilers | Industry - Other Combustion |
|---|---|---|---|---|---|---|
| BC1 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| BC2 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| HC1 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| HC2 | 1.46 | 1.03 | 1.46 | 1.46 | 1.46 | 1.46 |
| HC3 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 |
| DC | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 |
| OS1 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| OS2 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| HF | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 |
| MD | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| LF | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| GAS | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |

* See table 3.3 for a description of fuel abbreviations.

Table 4.7 Heat values of fuels by sector [GJ/metric ton]

| Fuel* | Conversion | Power Plants | Domestic | Transport | Industry - Boilers | Industry - Other Combustion |
|---|---|---|---|---|---|---|
| BC1 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 | 15.00 |
| BC2 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| HC1 | 29.00 | 29.00 | 29.00 | 29.00 | 29.00 | 29.00 |
| HC2 | 23.60 | 19.80 | 23.60 | 23.60 | 23.60 | 23.60 |
| HC3 | 17.00 | 17.00 | 17.00 | 17.00 | 17.00 | 17.00 |
| DC | 28.50 | 28.50 | 28.50 | 28.50 | 28.50 | 28.50 |
| OS1 | 16.00 | 16.00 | 16.00 | 16.00 | 16.00 | 16.00 |
| OS2 | 12.50 | 12.50 | 12.50 | 12.50 | 12.50 | 12.50 |
| HF | 40.70 | 40.70 | 40.70 | 40.70 | 40.70 | 40.70 |
| MD | 43.10 | 43.10 | 43.10 | 42.70 | 43.10 | 43.10 |
| LF | 43.10 | 43.10 | 43.10 | 43.10 | 43.10 | 43.10 |
| GAS | 39.00 | 39.00 | 39.00 | 39.00 | 39.00 | 39.00 |

* See Table 3.3 for a description of fuel abbreviations

Table 4.8 Sulfur retention in ash by fuel and sector [fraction]

| Fuel* | Conversion | Power Plants | Domestic | Transport | Industry - Boilers | Industry - Other Combustion |
|---|---|---|---|---|---|---|
| BC1 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| BC2 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| HC1 | 0.05 | 0.05 | 0.10 | 0.05 | 0.05 | 0.05 |
| HC2 | 0.05 | 0.08 | 0.30 | 0.03 | 0.15 | 0.15 |
| HC3 | 0.05 | 0.05 | 0.10 | 0.05 | 0.05 | 0.05 |
| DC | 0.05 | 0.05 | 0.10 | 0.05 | 0.05 | 0.05 |
| OS1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| OS2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

* See Table 3.3 for a description of fuel abbreviations

Table 4.9 Calculated emission factors by fuel and sector [kt $SO_2$/PJ]

| Fuel* | Conversion | Power Plants | Domestic | Transport | Industry - Boilers | Industry - Other Combustion |
|---|---|---|---|---|---|---|
| BC1 | 0.93 | 0.93 | 0.93 | 0.93 | 0.93 | 0.93 |
| BC2 | 4.20 | 4.20 | 4.20 | 4.20 | 4.20 | 4.20 |
| HC1 | 0.33 | 0.33 | 0.31 | 0.33 | 0.33 | 0.33 |
| HC2 | 1.18 | 0.96 | 0.87 | 0.87 | 1.05 | 1.05 |
| HC3 | 1.68 | 1.68 | 1.59 | 1.68 | 1.68 | 1.68 |
| DC | 0.61 | 0.61 | 0.57 | 0.61 | 0.61 | 0.10 |
| OS1 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| OS2 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| HF | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |
| MD | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| LF | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| GAS | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |

* See Table 3.3 for a description of fuel abbreviations

Point source emissions are estimated from fuel characteristics parameters and fuel consumption estimates specific to each source by a method similar to that described above for area sources. Data on fuel characteristics for the 355 LPS were initially collected by the Asian Energy Network and compiled by AIT as part of the ADB project. IIASA had the responsibility for final quality control. The process included considerable feedback and iteration among the institutions in the entire energy network. Missing data on LPS characteristics were developed by IIASA using information from the IEA Coal Research power stations directory (Manda *et al.*, 1994).

Examples of the fuel characteristics data for one LPS are provided in Table 4.10 for the Jianbi power plant (LPS26) located in the Jiangsu (JINU) region of China (CHIN). Similar data are available for all other large point sources and may be displayed using the features of the ENEM module.

Table 4.10 Fuel characteristics and $SO_2$ emission factors in the power plant/boiler section of a large point source

**Country: CHIN** **Region: JINU** **LPS: LPS26, Jianbi**

| Fuel | GJ/ton | %Sulfur | % Sulfur Retention | Emission Factor ($ktSO_2/PJ$) |
|---|---|---|---|---|
| HC2 | 19.20 | 1.18 | 0.05 | 1.17 |
| HF | 40.70 | 0.53 | 0.08 | 0.24 |

### 4.3.2 Regional and national emission totals

National emissions of $SO_2$ for the year 1990 as calculated by RAINS-ASIA are listed in Table 4.11. Total Asia-wide emissions for the base year 1990 are estimated to be about 34 million tonnes, which is in reasonable agreement with the gridded emissions inventory for 1987/88 described in Section 4.2. Table 4.12 lists $SO_2$ emissions in 1990 by region. Regions with significant emission totals include several regions in China (HEHE, JINU, NEPL, SICH) whose current emissions exceed two million tons of $SO_2$.

Sulfur dioxide emissions results calculated from alternative scenarios using the Low energy scenario and emission abatement technologies are presented in Chapter 7 on scenario results.

Table 4.11 $SO_2$ emissions in 1990 from area sources and LPS [kt $SO_2$]

| **Country** | **Area sources** | **LPS** | **Total** |
|---|---|---|---|
| Bangladesh | 118 | 0 | 118 |
| Bhutan | 2 | 0 | 2 |
| Brunei | 6 | 0 | 6 |
| Cambodia | 22 | 0 | 22 |
| China | 18,548 | 3,360 | 21,908 |
| Hongkong | 31 | 108 | 140 |
| India | 3,273 | 1,199 | 4,472 |
| Indonesia | 541 | 89 | 630 |
| Japan | 818 | 17 | 835 |
| Korea, North | 343 | 0 | 343 |
| Korea, South | 1,542 | 98 | 1,640 |
| Laos | 3 | 0 | 3 |
| Malaysia | 149 | 57 | 206 |
| Mongolia | 78 | 0 | 78 |
| Myanmar | 18 | 0 | 18 |
| Nepal | 122 | 0 | 122 |
| Pakistan | 614 | 0 | 614 |
| Philippines | 382 | 9 | 391 |
| Singapore | 191 | 0 | 191 |
| Sri Lanka | 42 | 0 | 42 |
| Taiwan | 478 | 21 | 500 |
| Thailand | 569 | 469 | 1,038 |
| Vietnam | 113 | 0 | 113 |
| International Shipping | 243 | 0 | 243 |
| Total | 28,247 | 5,428 | 33,675 |

Table 4.12 Total $SO_2$ emissions by region (area sources plus LPS) in 1990 [kt $SO_2$]

| COUNTRY | REGION | EMISSION | COUNTRY | REGION | EMISSION |
|---|---|---|---|---|---|
| Bangladesh | *Dhaka* | 17.0 | India (contd.) | Orissa | 190.5 |
| | Rest of Country | 101.0 | | Punjab-Chandigarh | 179.4 |
| Bhutan | | 1.5 | | Rajasthan | 161.0 |
| Brunei | | 6.3 | | Tamil Nadu-Pondicherry | 350.3 |
| Cambodia | | 22.2 | | Uttar Pradesh | 641.5 |
| China | *Beijing* | 270.3 | | Jammu-Kashmir-Himachal Pradesh | 23.2 |
| | *Chongqing* | 974.2 | Indonesia | *Jakarta* | 24.9 |
| | Fujian | 297.9 | | Java | 383.6 |
| | Guangdong-Hainan | 705.6 | | Rest of Country | 109.2 |
| | Guangxi | 800.7 | | Sumatra | 112.4 |
| | *Guangzhou* | 231.3 | Japan | Chugoku-Shikoku | 162.0 |
| | *Guiyang* | 340.2 | | Chubu | 157.6 |
| | Guizhou | 785.6 | | Hokkaido-Tohoku | 110.2 |
| | Hebei-Anhui-Henah | 3084.9 | | Kanto | 167.9 |
| | Hubei | 426.4 | | Kinki | 125.1 |
| | Hunan | 394.3 | | Kyushu-Okinawa | 112.7 |
| | Nei Mongolia-Ningxia | 689.8 | Korea-North | | 343.1 |
| | Jiangsu | 2108.6 | Korea-South | Northern Province | 246.2 |
| | Jiangxi | 334.6 | | *Pusan* | 606.0 |
| | Heilongjiang-Jilin-Liaoning | 2491.1 | | *Seoul-Inchon* | 499.1 |
| | *Shanghai* | 507.4 | | Southern Province | 289.0 |
| | *Shenyang* | 102.3 | Laos | | 3.4 |
| | Shaanxi-Gansu | 827.4 | Malaysia | *Kuala Lumpur* | 10.7 |
| | Shandong | 1061.9 | | Peninsula Malaysia. | 162.2 |
| | Shanxi | 632.4 | | Sarawak-Sabah | 32.7 |
| | Sichuan | 2336.1 | Mongolia | | 77.7 |
| | *Taiyuan* | 199.8 | Myanmar | | 18.1 |
| | *Tianjin* | 231.8 | Nepal | | 122.3 |
| | Tibet-Quinghai-Xinjiang Uygur | 348.1 | Pakistan | *Karachi* | 105.1 |
| | *Wuhan* | 316.1 | | *Lahore* | 20.7 |
| | Yunnan | 874.9 | | NW Frontier Provinces-Baiuchistan | 102.1 |
| | Zhejiang | 534.5 | | Punjab | 285.1 |
| Hongkong | | 139.6 | | Sind | 101.1 |
| India | Andhra Pradesh | 388.1 | Philippines | Bicol-Visayas.-Mindanao | 85.5 |
| | West Bengal | 222.3 | | Luzon | 172.6 |
| | Bihar | 363.1 | | *Metro Manilla* | 132.7 |
| | *Bombay* | 140.7 | Singapore | | 190.9 |
| | *Calcutta* | 39.4 | Sri Lanka | | 41.9 |
| | *Delhi* | 44.6 | Taiwan | | 499.5 |
| | East Himalayas: Asam-NE Highlands | 66.5 | Thailand | *Bangkok Metro Region* | 285.0 |
| | Gujarat | 388.9 | | Central Valley | 124.2 |
| | Haryana | 101.5 | | NE Plateau | 51.6 |
| | Karnataka-Goa | 134.1 | | N. Highlands | 521.1 |
| | Kerala | 55.2 | | South Peninsula | 55.8 |
| | *Madras* | 49.5 | Vietnam | North | 55.1 |
| | Maharasthra-Dadra Nagar-Haveli-Daman-Diu | 520.0 | | South | 58.1 |
| | Madhya Pradesh | 412.1 | International Shipping | | 243.3 |
| | | | TOTAL | | 33,674.7 |

*Note: Italicized regions indicate the 22 large urban areas, "megacities".*

## 4.4 *Technical emission control options and costs*

A powerful feature of the RAINS-ASIA model is its capability to explore the effects and costs of emission reduction strategies. Defining a control strategy means prescribing certain emission control measures for specific emission sources. Reduction strategies can be oriented towards entire regions or countries, towards individual plants (e.g., for any of the 355 large point sources contained in the RAINS-ASIA database), to whole economic sectors considered in the database (e.g., for fuel use in the domestic sector, certain industries, etc.) or to specific fuel types (e.g., for high sulfur hard coal).

The following groups of emission control options are considered in the RESGEN and RAINS-ASIA models:

- energy conservation,
- substitution of fuels containing sulfur by those with less or no sulfur,
- desulfurization of fuels before combustion,
- desulfurization during and after combustion.

The first two emission control options, energy conservation and fuel substitution, relate directly to assumptions developed in the construction of energy scenarios. Hence, these options for emissions reductions are explored in the energy scenario generation module (RESGEN), and thus only receive brief treatment in this section (see Chapter 3).

Energy conservation is a strong and cost-effective option to reduce emissions. Often it produces a variety of other positive effects in addition to emission reductions, e.g., the replacement of ineffective capital stock and a reduction in overall energy demand that, in turn, have consequences on trade balances, etc. Energy conservation strategies are developed as part of the energy scenario development process in the RESGEN model. Alternative energy scenarios may be developed which can incorporate a wide variety of assumptions regarding energy consumption and more efficient use of energy. The result of such assumptions is lower energy demand, less fossil fuel combustion and lower emissions.

Similarly fuel substitution can also be a very effective means for reducing emissions. Substitution of low emission fuels such as natural gas for high emission fuels like coal in the energy consuming sectors has been demonstrated to be a very effective emissions control option in many industrialized countries. Fuel substitution options of this type are an integral part of the energy scenario development process and the means for implementing these assumptions is incorporated in the RESGEN model.

Desulfurization before, during or after combustion is directly related to reducing $SO_2$ emissions. Consequently, these types of options are treated in the energy and emissions (ENEM) module of RAINS-ASIA, neglecting, as a first order estimate, their feedbacks on the energy system.

This remainder of this section provides a brief description of the technical options to reduce $SO_2$ emissions available in the ENEM module. The measures include:

- using low sulfur hard coal, either by utilizing naturally occurring low sulfur coal grades or, to a certain extent, by coal washing,

- using heavy fuel oil with low sulfur content, again either produced from low sulfur crudes or oil desulfurized during the refining process,
- using gas oil (diesel oil) with lower sulfur content,
- introducing desulfurization during the combustion process, e.g., by injecting of limestone into the furnace or by various types of fluidized bed combustion,
- introducing desulfurization of the flue gas after combustion.

Since it is difficult - and not very useful - to describe dozens of commercially available processes without knowing the specific applicability to each individual emission source represented in RAINS-ASIA, the model groups the technologies into categories that describe their major technical and economic features. In practice, for each of the technology categories, one representative process has been selected and introduced into the model. The technical options to reduce $SO_2$ emissions included in ENEM are shown in Table 4.13.

Table 4.13 Technical options to reduce $SO_2$ emissions considered in ENEM

| **Technical $SO_2$ Control Option** | **$SO_2$ Removal Efficiency or Final S% Achieved** |
|---|---|
| Oil Desulfurization / Heavy Fuel Oil | 0.6 % S |
| Oil Desulfurization / Diesel | 0.3-0.05 % S |
| Low Sulfur Coal | 0.6 % S |
| Coal Washing | 50 % |
| Limestone Injection or Fluidized Bed Combustion | 50 % |
| Wet Limestone Scrubbing (FGD) | 90 % |
| Regenerative Processes | 98 % |

The ENEM module also performs an economic assessment of emission reduction strategies, limited to the costs of applying emission control technologies. The purpose of this analysis is to provide a consistent basis for comparing of emission control costs:

- among various countries, and
- among different energy and emission control scenarios.

To enable international comparability of the cost estimates, the model uses the US dollar of 1990 as a common currency unit.

In summary, the computer implementation of ENEM enables the user to:

- review the energy balances for the various energy pathways developed with RESGEN;
- specify and store 'control strategies', i.e., combinations of emission control measures for any particular sector, fuel or individual large point source;

- develop 'emission control scenarios' by selective application of the various control strategies to any of the 95 regions considered in the RAINS-ASIA model, based on the specified energy pathway;
- explore $SO_2$ emissions for any of the emission control scenarios, aggregated by region, economic sector, fuel type or for individual large point sources;
- estimate emission control costs of the emission scenarios, for any combination of sectors, fuels and technologies; and
- identify the cost-minimal combination of control measures to reach certain emission limits in a particular region.

### 4.4.1 Low sulfur fuels and fuel desulfurization

A major group of measures to reduce $SO_2$ emissions focuses on reducing the sulfur content of fuels either by using naturally occurring low-sulfur fuels or through desulfurization treatment of the fuels. Despite the large number of currently commercially available and potential future processes for reducing the sulfur content in fuels, the RAINS-ASIA model restricts itself to the main technological and economic characteristics of the most relevant options. Without keeping track of eventually necessary investments, e.g., in the refinery sector, the model only takes account of the resulting price differentials for fuel grades with reduced sulfur contents. Because of the basic assumption of a free international market for energy and desulfurization technology, these price increments are considered valid for all countries throughout the region. In particular, RAINS-ASIA considers:

- low sulfur hard coal,
- low sulfur heavy fuel oil, and
- low sulfur gas oil.

In RAINS-ASIA, low-sulfur hard coal is assumed to have a minimum sulfur content of 0.6 percent. This definition might appear conservative. It is, however, justified by concerns about supply constraints for low-sulfur coal on the world market should this become a major long-term option for important world coal consumers. The costs related to this option are derived from an analysis of the long-term price differences on the world coal market (Amann, 1990). The model also enables the formulation of strategies aimed at less ambitious reductions of the sulfur content in coal, such as those achievable by coal washing.

Desulfurization of liquid fuels affects various oil products in different ways. The light fraction products (gasoline, jet fuel) contain a negligible amount of sulfur. For middle distillates (gas oil, diesel) two desulfurization steps are described in the model: a low-cost desulfurization bringing the sulfur content down to 0.3 percent, and a second step reducing it further to 0.05 percent at higher costs. The desulfurization of heavy fuel oil is considered to be economically competitive down to 0.6 percent sulfur content at costs determined by the refinery process. It is assumed that these costs will also determine the price difference of heavy fuel oil refined from low-sulfur crudes.

The actual cost data used in RAINS-ASIA are shown in Table 4.14. Basic data have been derived from OECD publications (OECD, 1987) and verified against current market observations (Pototschnig, 1993). Cost assumptions for desulfurization of gas oil and diesel oil have been confirmed by Kroon (1992).

Table 4.14 Price differentials for low sulfur fuels

| Fuel type | Price difference (million US\$/PJ/%S$^{1)}$) | Typical heating value, GJ/t | Cost/t $SO_2$ removed (US\$/t $SO_2$) |
|---|---|---|---|
| Hard coal and coke, 0.6 % sulfur | 0.34 | 27.0 | 482$^{2)}$ |
| Heavy fuel oil, 0.6 % sulfur | 0.54 | 41.5 | 1111 |
| Gas oil | | | |
| - reduction to 0.3 % sulfur | 0.84 | 42.5 | 1784 |
| - reduction to 0.05 % sulfur | 2.52 | 42.5 | 5352 |

### 4.4.2 Desulfurization during or after combustion

Desulfurization during combustion and purification of the flue gases after fuel combustion require measures at the plant site (Amann, 1990). To represent the wide spectrum of currently available and future control technologies and the large variation in cost efficiencies, three techniques with different cost characteristics and removal rates have been selected for RAINS-ASIA:

- desulfurization during combustion with removal efficiencies of about 50 percent at relatively low investments and operating costs (e.g., limestone injection, fluidized bed combustion and various technological approaches that are currently under development in some Asian countries),
- the most commonly used wet flue gas desulfurization process with typical sulfur removal rates of 90 percent at comparably moderate costs (e.g., wet limestone scrubbing, spray dryer processes, etc.), and
- regenerative flue gas purification with emission reductions of up to 98 percent, at relatively high costs.

For each category, there are several competing technologies. To simplify the cost assessment in RAINS-ASIA, the model confines itself to the most commonly used technology in each category. In a competitive market, other potential technologies must overrule the market leaders at least in terms of cost and removal efficiencies, unless national preferences dominate these criteria. Such national considerations, however, should not be used for an international comparative assessment as envisaged in the RAINS-ASIA model.

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[1] % S reduced compared to original fuel.

[2] Calculated on an assumption that 5 percent of S is retained in the ash.

### Limestone injection

$SO_2$ can be captured as it forms during combustion if a $SO_2$ sorbent such as calcium carbonate (limestone) is present. Removal is usually accomplished by adding $SO_2$ sorbents to the coal pellets in stoker boilers, by injection of sorbents into pulverized coal-fired boilers, or by fluidized bed combustion. The most common process currently in use, the limestone injection process, was selected to represent the cost-efficiency ratio. This technology achieves emission reduction rates of 50 to 60 percent at moderate investments, making it an attractive option for countries with capital shortage or power plants designed to operate intermittently.

Characteristic to many of these technologies is that they require a high sorbent-to-sulfur ratio to achieve sufficient reduction rates. Consequently, such technologies produce large amounts of waste material, the disposal of which faces increasing difficulties.

### The wet limestone flue gas desulfurization method and the Wellman-Lord process

A large variety of flue gas purification processes are available on a commercial basis. Over the last few years, the wet limestone scrubbing process has gained a dominant position on the world market. Flue gas is brought into close contact with a limestone suspension, which reacts with the sulfur in the flue gas to form gypsum as a by-product. Gypsum can be further used, e.g., for producing building material. Sulfur removal rates of between 90 and 95 percent are typical (IEA, 1988).

To mark the high-end of advanced $SO_2$ control options, the RAINS-ASIA model also considers the Wellman-Lord process as a characteristic high-efficiency regenerative technology without production of waste material. Using NaOH as a sorbent the captured sulfur can be further used in the chemical industry.

### Cost evaluation

Common to all these desulfurization processes is that they require investments at the plant site. In the long-term analysis carried out in the RAINS-ASIA model, however, the emphasis lies on total life-cycle costs of the equipment rather than on short-term considerations of capital demand. Consequently, using the internationally recommended standard investment analysis method (OECD, 1986) as a guideline, the RAINS-ASIA model estimates life cycle costs from three components (I) investment related costs, (ii) fixed operating costs and (iii) variable operating and maintenance costs.

### Investments

Investments include the expenditure accumulated until the start-up of an installation, such as delivery of the installation, construction, civil works, ducting, engineering and consulting, license fees, land requirement, working capital.

The model aggregates these items into an investment function $I$, providing for eventual economies of scale (Equation 1). The necessary size of an abatement installation for a certain plant capacity $bs$ is derived from the fuel-specific flue gas volume $v$ to be handled. The form of the function is described by its coefficients $ci^f$ and $ci^v$. Additional costs due to site-specific difficulties for retrofit applications to existing plants can be reflected by the retrofit cost factor $r$. This factor determines a percentage increase of investments for the retrofit case compared to the cost of a new plant. The investment functions used in RAINS-ASIA are scaled to thermal input capacities of boilers/furnaces ($MW_{thinp}$).

$$I = (ci^f + \frac{ci^v}{bs}) \times v \times (1+r) \qquad (1)$$

In order to derive life cycle costs of installations the investments are annualized over the plant lifetime $lt$, using the interest rate $q$($q$ is expressed as %/100):

$$I^{an} = I \times \frac{(1+q)^{lt} \times q}{(1+q)^{lt} - 1} \qquad (4)$$

### Fixed operating costs

The annual fixed expenditures $OM^{fix}$ cover maintenance, taxes and administrative overhead. These cost items are not related to the actual use of the plant. As a rough estimate for such annual expenditures, most technical standards use a standard percentage $f$ of the total investments:

$$OM^{fix} = I \times f \qquad (5)$$

### Variable operating costs

Variable operating costs $OM^{var}$ are related to the actual operation of the plant and take into account

- additional labor requirement,
- increased energy demand for operating the device (e.g., for the fans and for reheating),
- sorbent material demand (e.g., limestone),
- waste disposal,
- etc.

These cost items are calculated based on the specific demand $\lambda^x$ of a certain control technology and its (country-specific) price $c^x$:

$$OM^{var} = (\lambda^l c^l / pf + \lambda^e c^e) + ef \times x \times (\lambda^s c^s + \lambda^d c^d) \qquad (4)$$

$$ef = 2 \times \frac{sc}{hv} \times (1 - sr)$$

with

| | |
|---|---|
| $\lambda^l$ | labor demand |
| $\lambda^e$ | additional electricity demand |
| $\lambda^s$ | sorbents demand |
| $\lambda^d$ | amount of waste |
| $c^l$ | labor cost |
| $c^e$ | electricity price |
| $c^s$ | sorbents price |
| $c^d$ | costs for waste disposal, |
| $ef$ | implicit $SO_2$ emission factor |
| $x$ | removal efficiency |
| $sc$ | sulfur content |
| $hv$ | heat value |
| $sr$ | sulfur retention in ash |

### Unit costs of $SO_2$ control

Equation 5 relates all cost items to one unit of fuel input ($c_{PJ}$); in the case of investment related costs the capacity utilization factor *pf* (operating hours/year) is used. For individual plants (e.g., the large point sources distinguished in RAINS-ASIA the plant factor is modeled as a function of time, taking account of declining capacity utilization towards the end of the technical life time, when power stations are gradually phased out.

$$c_{PJ} = \frac{I^{an} + OM^{fix}}{pf} + OM^{var} \qquad (5)$$

Although the cost coefficient $c_{PJ}$ is useful for the calculation of price effects on the product (e.g., on electricity), the cost efficiency of different control options can only be evaluated by relating the abatement costs to the amount of reduced $SO_2$ emissions ($c_{SO2}$). For this purpose Equation 6 is used:

$$c_{SO_2} = c_{PJ} \,/\, ( ef \times x) \qquad (6)$$

### Data for cost calculation

The parameters used in the equations above can be split into two groups:

- **Common parameters** are assumed to be equal for all countries under consideration. They can be divided into the *general* and *technology-specific* parameters (Table 4.15). General parameters are valid for all technologies. Technology-specific parameters describe the typical economic and technical properties of control technologies. This group comprises *technical* (removal efficiency, requirements for energy and sorbents material) and *economic* parameters (e.g., used in the investment function, and for calculating retrofit and maintenance costs).

- **Country-specific** parameters (Table 4.16) consider conditions in individual countries under which abatement technologies have to be applied. The most important parameters are the average capacity utilization of plants, the average boiler/furnace size and the prices for energy and material consumption.

Table 4.15 Common parameters used for the $SO_2$ control cost calculation

| Symbol | Item | Unit |
|---|---|---|
| ***General parameters:*** | | |
| $v$ | Relative flue gas volume[3] | - |
| $lt$ | Lifetime of installation | years |
| ***Technology specific parameters:*** | | |
| $I$ | Investment function | US\$/kW$_{thinp}$[4] |
| $ci^f$ | Intercept | US\$/kW$_{thinp}$ |
| $ci^v$ | Slope | $10^3$ US\$ |
| $f$ | Maintenance costs and overheads | %/100/year |
| $\lambda^e$ | Specific demand for energy | GWh/PJ$_{thinp}$ |
| $\lambda^l$ | Specific demand for labor | man-yr/MW$_{thinp}$ |
| $\lambda^s$, $\lambda^d$ | Specific demand for sorbents and waste disposal | ton/t $SO_2$ removed |
| $x$ | Sulfur removal efficiency | %/100 |
| $r$ | Retrofit cost factor | %/100 |

---

[3] Relative to hard coal fired boilers.

[4] kW$_{thinp}$ - kilowatt thermal (fuel) input to the boiler/furnace.

Table 4.16 Country specific parameters

| Symbol | Item | Unit |
|---|---|---|
| $sc$ | Sulfur content | %/100 |
| $hv$ | Heat value (lower) | GJ/t |
| $sr$ | Sulfur retained in ash | %/100 |
| $bs$ | Average boiler size | MW$_{thinp}$ |
| $pf$ | Capacity utilization | hours/year |
| $q$ | Real interest rate | %/100 |
| $c^e$ | Electricity price | US\$/kWh |
| $c^l$ | Labor price | US\$/man-yr |
| $c^s$, $c^d$ | Sorbents and waste disposal prices | US\$/ton |

**Data sources**

Although the cost evaluation method outlined above is based on international standard procedures, it still remains a difficult task to identify appropriate parameter values leading to accurate estimates of future $SO_2$ emission control costs in Asia.

After initial discrepancies in national cost estimates (for an early discussion of the differences among estimates for U.S., Japan and Germany see e.g., OECD, 1986), technology related data for world wide technologies are now converging (Dace *et al.*, 1986) and show a stabilizing trend (Schärer, 1993). Consequently, characteristic values confirmed for Western or Japanese technologies could be considered representative also for future applications in other Asian countries. General and technology specific data used in the RAINS-ASIA model are listed in Tables 4.17 and 4.18.

Table 4.17 Data used in the cost calculations for general parameters

| Item | Value |
|---|---|
| Relative flue gas volume($v$) | (Hard coal = 1) |
| Brown coal | 1.2 |
| Hard coal | 1.0 |
| Heavy fuel oil | 0.9 |
| Lifetime ($lt$) | (years) |
| - for existing power plants | 20 |
| - for new power plants | 30 |
| - for industry | 20 |

Table 4.18 Technology specific data

| Item | Symbol | Combustion Modification (limestone injection) | | Wet Flue Gas Desulfurization | | Regenerative Processes | Units |
|---|---|---|---|---|---|---|---|
| | | new | retrofit | new | retrofit | new | |
| **Investment function:** | | | | | | | |
| Intercept | $ci^f$ | 22 | 29 | 44 | 57 | 116 | $\mathrm{US\$/kW_{thinp}}$ |
| Slope | $ci^v$ | 3,700 | 4,815 | 12,350 | 16,050 | 24,570 | $10^3$ US$ |
| Resulting specific investments for a 580 $\mathrm{MW_{thinp}}$ plant[5)] | | 28 | 38 | 65 | 85 | 159 | $\mathrm{US\$/kW_{thinp}}$ |
| **Operating costs:** | | | | | | | |
| Annual maintenance costs | $f$ | 4.0 | | 4.0 | | 4.0 | % of total investments/year |
| Labor demand | $\lambda^l$ | 10.8 | | 10.8 | | 25.2 | man-year/$\mathrm{GW_{thinp}}$ |
| Additional energy demand | $\lambda^e$ | 0.5 | | 1.0 | | 2.2 | $\mathrm{GWh/PJ_{thinp}}$ |
| Sorbents | | Limestone | | Limestone | | NaOH | |
| Sorbents demand | $\lambda^s$ | 4.68 | | 1.56 | | 0.01 | t/t $SO_2$ removed |
| By-product | | Sludge | | Gypsum | | Sulfur | |
| Amount of by-product | $\lambda^d$ | 7.80 | | 2.60 | | 0.50 | t product/t $SO_2$ removed |
| Sulfur removal efficiency | $x$ | 50.0 | | 95 | | 98.0 | % |

## 4.4.3 Control of process emissions

Process emissions[6)] are caused by various types of industrial sources. Thus it is difficult to estimate detailed control costs for this group of emitters. Therefore, a simplified approach has been adopted based on the assumption that process emissions can be removed up to a certain percentage of the uncontrolled emissions at step-wise increasing costs. Three such cost categories have been implemented. The costs for each step are shown in Table 4.19.

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[5)] An equivalent of about 210 MW electric for a power plant.

[6)] For definition of process emissions in RAINS-ASIA, see Bertok et al., 1993.

Table 4.19 Control costs for process emissions

| Control option | Removal efficiency, % | Unit cost, US$/t $SO_2$ |
|---|---|---|
| Stage 1 | 50 | 432 |
| Stage 2 | 70 | 503 |
| Stage 3 | 80 | 633 |

## 4.4.4 Cost curves for $SO_2$ reduction

The RAINS-ASIA model also provides an option to calculate cost curves for reducing $SO_2$ in particular regions or countries. Such curves provide the minimum cost of achieving emission reductions for each abatement level, using the cost-optimal combination of abatement measures. Cost curves are compiled by ranking available emission control options for the various sources according to their cost-effectiveness and combining them with the potential for emission reductions determined by the properties of the fuel and the abatement technologies.

Consequently, the shape of such curves is influenced by the costs of applying the various emission control measures in a region (e.g., represented by cost coefficients according to Equation 6) and the potential for emission reductions determined by fuel characteristics and the selected energy pathway.

The RAINS-ASIA model computes two types of cost curves:

The **'total cost'** curve displays total annual costs to achieve certain emission levels in a region. These curves are piece-wise linear, with the slopes of the individual segments determined by the costs of applying the various technologies.

The **'marginal cost'** curve is a step-function, indicating the marginal costs (i.e., the costs for reducing the last unit of emissions) at the various reduction levels.

The current implementation of RAINS-ASIA creates cost curves only for the available emission control options, i.e., measures already implemented are excluded from the consideration. Thus, to obtain the overall costs of measures in a selected region, cost curves have to be based on the 'no-control' scenario, otherwise the costs of already existing installations would be ignored. An example cost curve for the N Highlands (NHIG) region of Thailand is presented in Figure 4.4.

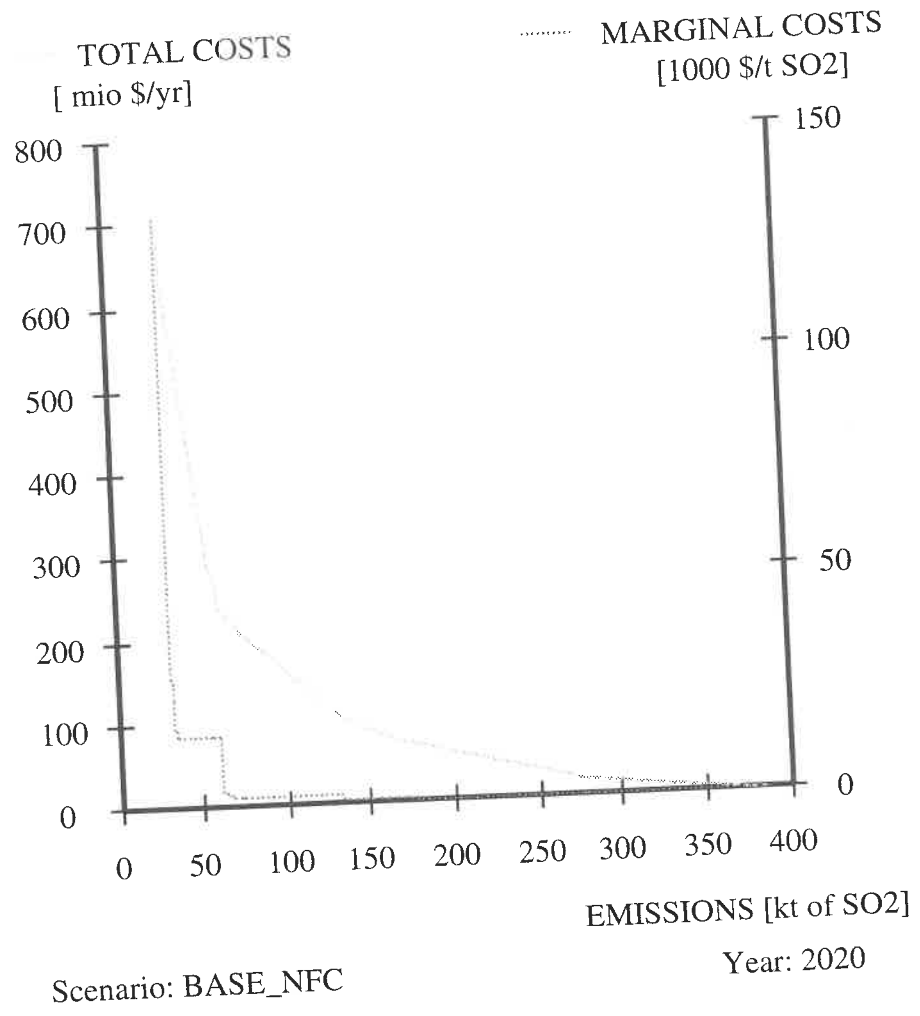

Figure 4.4 Example cost curves for the NHIG region of Thailand for the baseline energy scenario

### 4.6 *Conclusions and recommendations*

A comprehensive analysis of the current picture of sulfur dioxide emissions in Asia has been assembled for the RAINS-ASIA project. In addition, tools have been developed to project future emissions and the potential to reduce those emissions through application of control technologies and other methods. Having said this, there is still a critical need to improve, update, and extend the existing work.

In order to better anchor the future emissions forecasts, a revised, self-consistent, base-year inventory should be assembled for a more recent year, say, 1992. Any discrepancies between this work and the data of Akimoto and Narita need to be understood and reconciled. In addition, the energy data developed by the Asian network needs to be cross-checked and verified against the base-year inventory. In future work, it will be important to add emissions of nitrogen oxides, in order to obtain a complete picture of acidifying pollutants and to be able to assess the urban air pollution situation. This will necessitate new emphasis on the transportation sector. Finally, the emission factors used in the base-year inventory and in the RAINS-ASIA model need to be harmonized. Discussions have also taken place regarding extension of the methodology to include other pollutants or gases, such as carbon dioxide, methane, particulate matter, and ammonia. Decisions on these matters await resolution of future funding levels and direction of the project.

As the project moves into the phase of assessing costs and emissions under future scenarios, it is important that RAINS-ASIA uses appropriate technologies for the Asian context and also appropriate cost, performance, and application data for these technologies. Note that in Phase I the technology characteristics are largely based on European and North American experience. An Asian technology characterization data base is needed that could be used within the model and also for stand-alone analyses. At a minimum, this data base would include low-cost technologies that are not typically analyzed in the West (e.g., coal briquetting, CFBC, and wet particle scrubbers), low-cost adaptations of western technology, and appropriate technologies for Asian energy resources (Thai lignite, high-ash Indian coals, etc.). Costs would also reflect regional costs for labor and materials, as appropriate. The data base would include both energy production and emission control technologies.

## REFERENCES

Acid News, 1989. Swedish NGO Secretariat on Acid Rain, Stockholm, Sweden. July.

Amann, M., 1990 Energy use, emissions and abatement costs in Europe. In: J. Alcamo, R.W. Shaw and L. Hordijk (eds), *The RAINS Model of Acidification, Science and Strategies in Europe*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Akimoto H., and H. Narita, 1994, *Atmospheric Environment 28* (2):213-225.

Asian Development Bank, 1991, *Environmental Considerations in Energy Development.*

Bertok, I., J. Cofala, Z. Klimont, W. Schöpp, M. Amann, 1993, *Structure of the RAINS 7.0 Energy and Emissions Database*. WP-93-67 IIASA, Laxenburg, Austria.

CONCAWE, 1993, *The European Environmental and Refining Implications of Reducing the Sulphur Content of Marine Bunker Fuels.* Report No. 1/93, Brussels, Belgium.

Dace, P.W. and D.R. Cope, 1986, *Flue gas desulphurization - system performance.* International Energy Agency, Coal Research, London, U.K.

Fearnresearch, 1988, *Fearnley's World Bulk Trades 1988*, Oslo, Norway.

Institute of Shipping Economics and Logistics, 1992, *Shipping Statistics Yearbook 1992*, Bremen, Germany.

International Atomic Energy Agency, 1988, *Experience with WASP and MAED Among IAEA Member States Participating in the Regional Co-operative Agreement (RCA) in Asia and the Pacific Region.* Report IAEA-TECDOC-528.

International Atomic Energy Agency, 1991, *Experience in Energy, Electricity, and Nuclear Power Planning with Emphasis on MAED and WASP Among Member States of the Regional Co-operative Agreement (RCA) in Asia and the Pacific Region.* Report IAEA-TECDOC-622.

International Energy Agency, 1988, *Emission Controls in Electricity Generation and Industry*. OECD, Paris

International Energy Agency, 1989, *World Energy Statistics and Balances*. OECD, Paris, France.

International Energy Agency, 1993, *Energy Prices and Taxes, fourth Quarter 1992*. OECD Paris, France.

Joshi, V., 1991, Biomass Burning in India. In: *Global Biomass Burning*, Joel S. Levine, *ed.* MIT Press, Cambridge, MA. pp. 185-193.

Kroon, P., 1992 *Notes about oil gasification and emission reduction of cars*. ESC - Energy Studies, Netherlands Energy Research Foundation (ECN), Petten, The Netherlands. (manuscript)

Manda, C.W., A.T. Kirchner, M. Daniel, O. Monfort, 1994, *World Coal-fired Power Stations: Africa, Asia and Australia*. International Energy Agency Coal Research, London

Mannini, A., M. Daniel, A. Kirchner, and H. Soud, 1990, *World Coal-Fired Power Stations*. IEA Coal Research, London, U.K.

Minerals Yearbook, 1989.

Norwegian Meteorological Institute, 1990, *Calculated Budgets of Airborne Sulphur and Nitrogen over Europe.* EMEP MSC-W Report 2/90, Oslo, Norway.

OECD, 1986, *Understanding Pollution Control Cost Estimates*. OECD Environmental Monographs, Vol. 1, Paris.

Pototschnig, A., 1994, Economic instruments for the control of acid rain in Britain. In: G. Klaassen and F. Forsund (eds), *Economic Instruments For Air Pollution Control*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Schärer, B., 1993, Technologies to clean up power plants. Experience with a DM 21 Billion FGD and SCR retrofit programme in Germany, Part 1 and 2. *Staub - Reinhaltung der Luft 53*, 87-92 and 157-160.

Smith, K., 1988, Air Pollution. Assessing Total Exposure in Developing Countries. *Environment 30* (10):16-20, 28-35.

Spiro, *et al.*, 1992, *Journal of Geophysical Research 97*, 6023-6036.

Stopford, M., 1988, *Maritime Economics.* Unwin Hyman Ltd., London, U.K.

United Nations, 1989, *Electric Power in Asia and the Pacific 1985 and 1986*. ESCAP Report No. ST/ESCAP/720.

United Nations, 1984, *Statistical Papers*. Maritime Transport Study. Series D.

U.S. Environmental Protection Agency, 1987a, *Criteria Pollutant Emission Factors for the 1985 NAPAP Emissions Inventory*. Report EPA-600/7-87/015.

U.S. Environmental Protection Agency, 1987b, *National Air Pollutant Emission Estimates, 1940-1985.* Report EPA-450/4-86-018.

The World Bank, 1992, *World Development Report 1992*. Oxford University Press, New York, USA.

World Energy Council, 1989, *Survey of Energy Resources*.

World Resources Institute, 1992, *World Resources 1992-93*, New York, U.S.A.

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# AN ASSESSMENT MODEL FOR AIR POLLUTION IN ASIA

## Chapter 5

## ATMOS Module

## Long Range Transport and Deposition of Sulfur in Asia

**Gregory Carmichael and Richard L. Arndt**

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