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

Chapter 7

Scenarios of Future Acidification in Asia: Exploratory Calculations

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7. SCENARIOS OF FUTURE ACIDIFICATION IN ASIA: EXPLORATORY CALCULATIONS

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7. SCENARIOS OF FUTURE ACIDIFICATION IN ASIA: EXPLORATORY CALCULATIONS

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7.1 Introduction

This chapter presents the results of an initial application of the Regional Air Pollution Information and Simulation (RAINS) model to explore the potential impacts on acidification of future scenarios of energy development in Asia. The purpose of these initial applications is twofold.

First, these scenarios provide the first regionally-disaggregated and integrative picture of the consequences of emissions and acid deposition under potential economic development and technological conditions for Asia during the coming two to three decades based on currently available knowledge.

Second, the scenario development provides a first practical test of the RAINS-Asia model, a new tool for the integrated assessment of sulfur emissions' impacts and abatement strategies for Asia.

The database upon which the scenarios are based represents an extensive collection and compilation effort carried out by a large number of institutions in Asia and Europe. The scenario generation process has provided an important step in sorting, organizing, assimilating, and updating that data – a process which is still underway and, in fact, never ends.

This chapter is organized as follows: Section 7.2 describes the baseline development of future energy use in Asia according to national expectations (the *base case* energy pathway). As an alternative, a scenario has been developed that explores the potential for increased energy efficiency and use of renewable resources (the *energy efficiency* pathway). Section 7.3 projects future sulfur emissions for the baseline energy scenario without further measures to control SO_2 emissions and analyzes regional sulfur deposition with critical loads, which have been defined in Chapter 6 of this report. Motivated by the serious threat imposed to many ecosystems by the uncontrolled growth of emissions, various features of the RAINS model are used to explore alternative strategies to keep sulfur deposition closer to critical loads. Section 7.4 examines costs and environmental impacts of a hypothetical strategy applying western emission standards to all Asian countries. Because of the high costs involved in such a policy, Section 7.5 applies advanced emission control measures only to the largest emission sources throughout the region. Since currently advanced control technologies are not legally required in most Asian countries, Section 7.6 investigates the costs and levels of ecosystem protection, if only domestically available emission control techniques would be applied. It will be shown that by selectively applying advanced measures to those areas, which have significant impacts on sensitive ecosystems, similar environmental impacts could be achieved at lower costs (Section 7.7). Section 7.8 demonstrates the capability of the RAINS model to identify impacts of individual emission sources and to relocate large point sources to less sensitive sites. Section 7.9 explores the implications of energy efficiency strategies. Conclusions are drawn in Section 7.10.

7.2 Energy pathways

To provide a basis for the analysis of emissions and emission control strategies, the RESGEN module of the RAINS model was used to develop two alternative energy pathways:

- The base case energy pathway, resembling 'business as usual' practices. This pathway assumes that each country would continue the current trends in energy policies, without strong promotion of energy efficiency measures or fuel substitution to reduce the emissions of acidifying pollutants. Efforts were made to utilize energy demand forecasts made by the government planning organizations or research institutions in each country. This pathway is the basis for the emission (control) scenarios analyzed in the following sections 7.3 to 7.8.

- An energy efficiency pathway. This pathway explores the possible reduction of emissions through a strong effort to use energy more efficiently. The efficiency improvements possible through to 2020 are based primarily on the experiences of the industrialized countries during the period 1973 – 1983 including the response to the sharp rise in energy prices, general improvements in technology, and increased use of renewable resources. The consequences of an energy efficiency pathway on SO_2 emissions and control costs are further explored in Section 7.9.

These two pathways are based on a variety of assumptions on socio-economic development, population growth, technological progress, etc., which are documented in Chapter 3 of this report. RESGEN was used to develop energy pathways for all 23 countries considered in RAINS-Asia. Furthermore, the data of the largest countries was disaggregated into sub-national regions, totalling 94 over all of Asia. Chapter 3 provides details on the RESGEN model.

Figures 7.1 and 7.2 display total primary energy consumption by fuel for the two pathways. Reflecting the current expectations in the countries, total primary energy consumption in the base case grows by 230 percent between 1990 and 2020 with a proportional increase in coal consumption. In the efficiency case, primary energy consumption grows by about 150 percent in the same period, with an even lower increase in coal use.

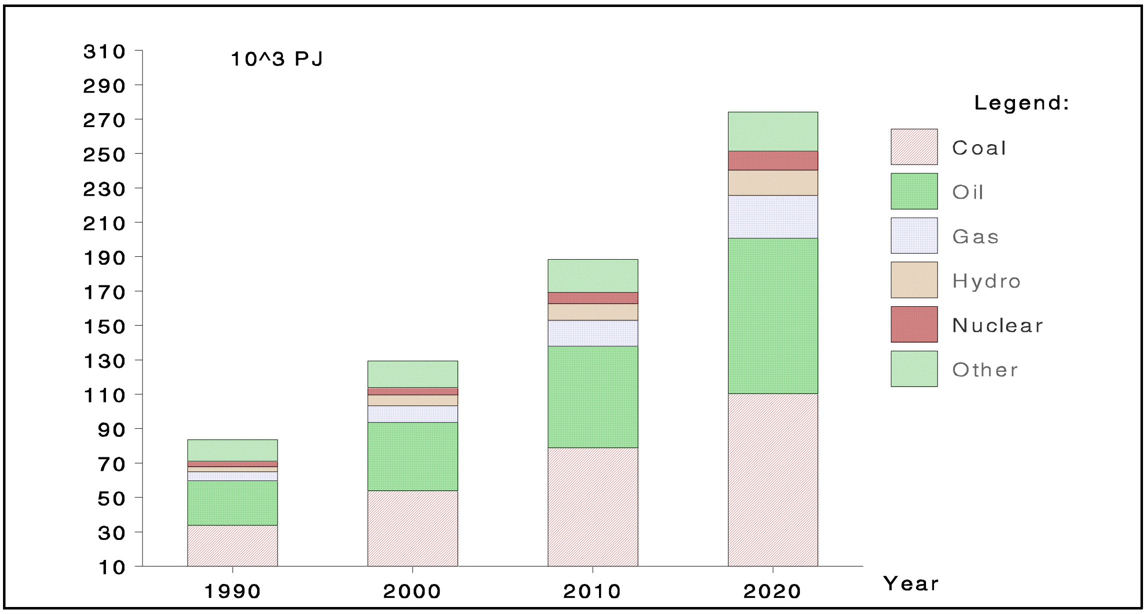

Figure 7.1 Primary energy consumption in the region, Base case energy pathway (1000 PJ)

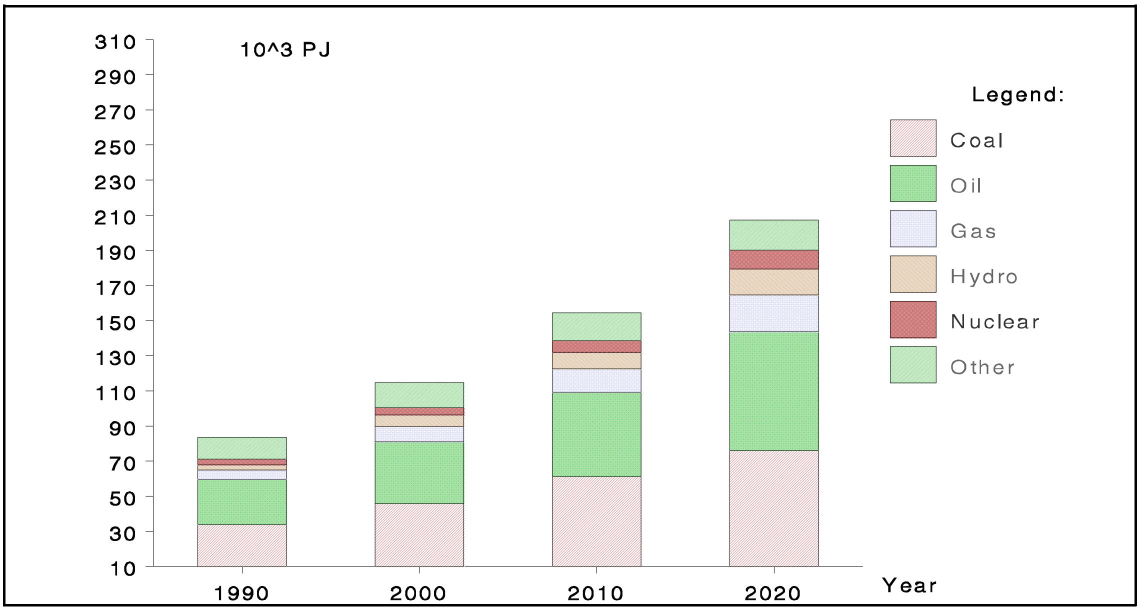

Figure 7.2 Primary energy consumption in the region, Energy efficiency pathway (1000 PJ)

7.3 A reference emission scenario: base case energy path without additional measures to control emissions

In order to provide a reference for the further analysis, an emission scenario has been developed based on the assumption that economic and energy development will follow the base case pathway and that -beyond the control measures required by current legislation in Japan and Taiwan - no further action will be taken for reducing SO_2 emissions. Due to the strong growth in economic activities and, subsequently, energy consumption assumed in the base case energy path, the lack of measures to limit emissions would lead to a significant increase in SO_2 emissions in the region: from 33.6 million tons in 1990 to more than 110 million tons in 2020, i.e., by about 230 percent. The increase in SO_2 emissions is strongly connected to the use of coal. Coal combustion is responsible for about three quarters of the total emissions over the whole period under study. About 20 percent of the emissions originate from the combustion of liquid fuels; the balance is a result of biomass combustion (Figure 7.3).

Figure 7.4 shows the development of emissions by economic sector. The highest growth in emissions comes from the power plant sector, due to the increased use of coal-based electricity generation. This sector's contribution to total emissions increases from 30 percent in 1990 to 37 percent in 2020. Thereby, also the relative importance of the various emission sources experiences an important change: whereas in 1990 about 16 percent of total SO_2 emissions in the region originated from the large point sources considered in the RAINS model (i.e., power stations with large boilers), in 2020 this share is expected to constitute about 25 percent of total emissions.

Differences among countries in the rates of economic development and the anticipated structures of the energy supply cause a regionally inhomogeneous picture of future emissions growth. In Japan, SO_2 emissions would increase by about 30 percent, whereas, e.g., in India, Indonesia, Philippines and Thailand the predicted expansions reach typically a factor of four to five (compare Table 7.1). For Pakistan, the expected growth in the consumption of high sulfur lignite would increase SO_2 emissions by a factor of 12, although compared to a low level in 1990.

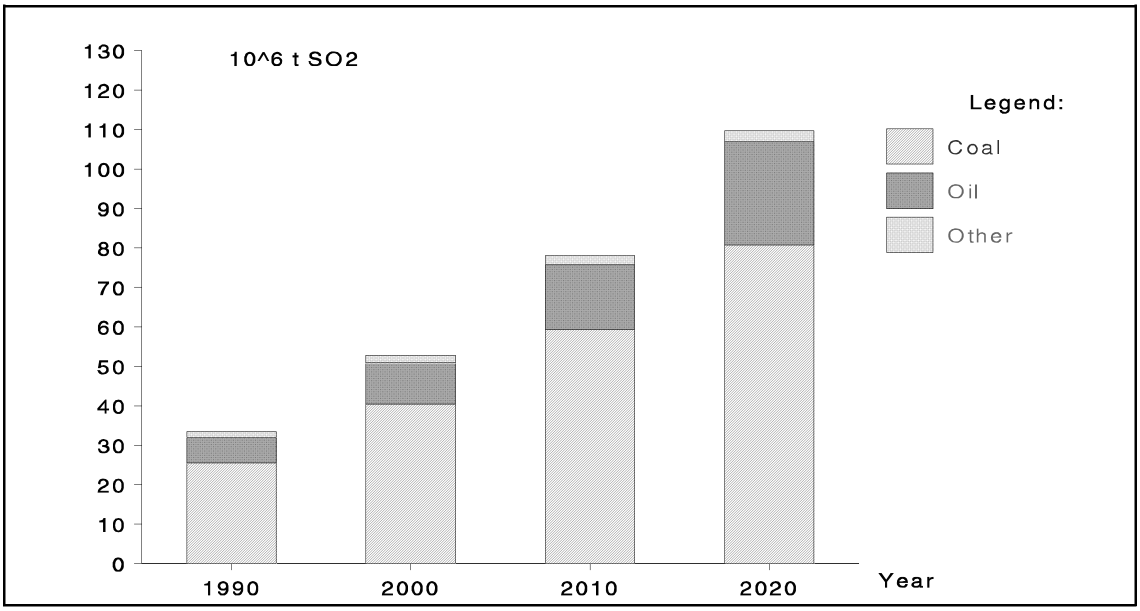

Figure 7.3 SO_2 emissions by fuel, reference scenario (million tons of SO_2)

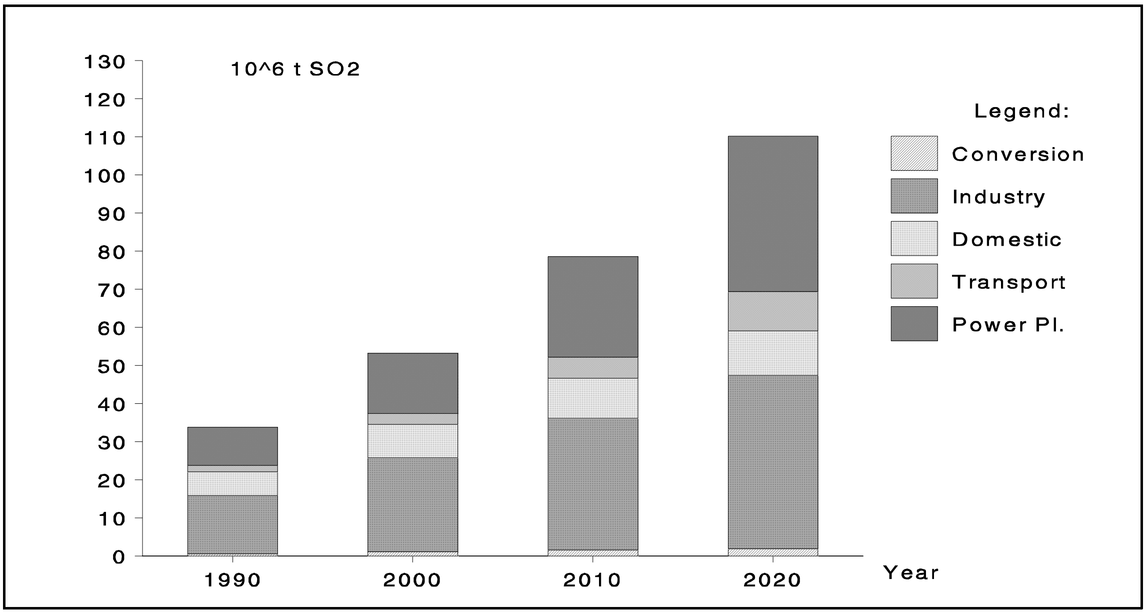

Figure 7.4 SO_2 emissions by sector, reference scenario (million tons of SO_2)

Table 7.1 SO_2 emissions in 1990 and for the reference scenario in the year 2020 (in thousand tons of SO_2)

	1990	**Reference scenario, 2020**	**Increase**
Bangladesh	118	524	344 %
Bhutan	2	12	500 %
Brunei	6	18	200 %
Cambodia	22	147	568 %
China	21908	60687	177 %
Hong Kong	140	378	170 %
India	4471	18549	315 %
Indonesia	630	3162	402 %
Japan	835	1120	34 %
Korea, north	343	1345	292 %
Korea, south	1640	5537	238 %
Laos	3	12	300 %
Malaysia	205	409	100 %
Mongolia	78	168	115 %
Myanmar	18	40	122 %
Nepal	122	247	102 %
Pakistan	614	7527	1126 %
Philippines	390	2037	422 %
Sea lanes	243	511	110 %
Singapore	191	1033	441 %
Sri Lanka	42	239	469 %
Taiwan	500	1478	196 %
Thailand	1038	4637	347 %
Vietnam	113	654	479 %
TOTAL	33674	110477	228 %

7.3.1 Sulfur deposition

The boost in SO_2 emissions resulting from the high growth in energy consumption will cause a strong increase in sulfur deposition throughout the region. In 2020, virtually all eastern parts of China and large regions in India would experience deposition between two and five grams. In many industrialized and metropolitan areas in Thailand, the Philippines and Malaysia sulfur deposition will exceed five grams to ten grams per square meter and year. Peak deposition of sulfur would escalate in some industrialized areas in China to about 26 grams per square meter and year (Figure 7.5). For comparison, sulfur deposition observed in the well-known industrial areas of Central and Eastern Europe peaked at about 15 grams per square meter and year.

Figure 7.6 reveals a significant change in deposition for almost all of Asia: In major areas in eastern and southern China and in some parts of Japan, sulfur deposition will increase by a factor of two to three, with places with increases of up to a factor of five. A factor of five is also observed in many regions India, Korea and Thailand. There are, however, also several sites in Asia for which an increase in sulfur deposition up to a factor of ten has to be expected. It should be mentioned that changes in emissions from outside the region (e.g., from Siberia) are not taken into account for this analysis.

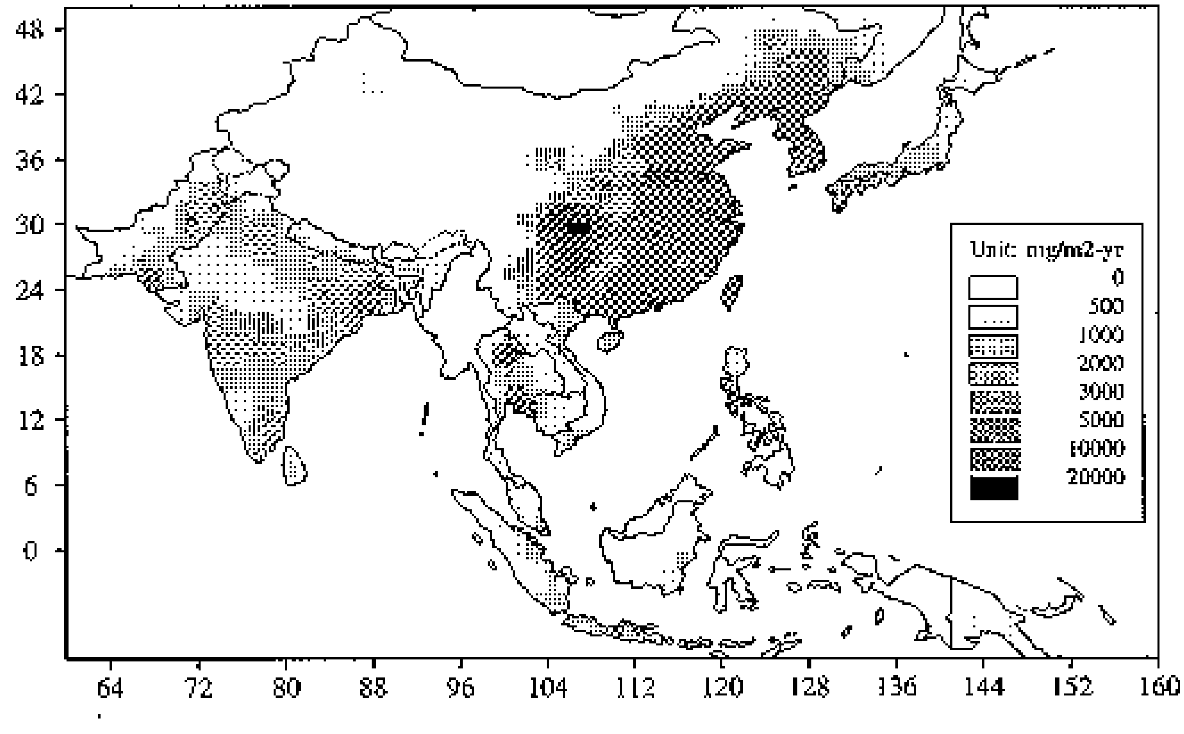

Figure 7.5 Sulfur deposition in 2020, Reference scenario (base case energy pathway, no further measures beyond current legislation assumed)

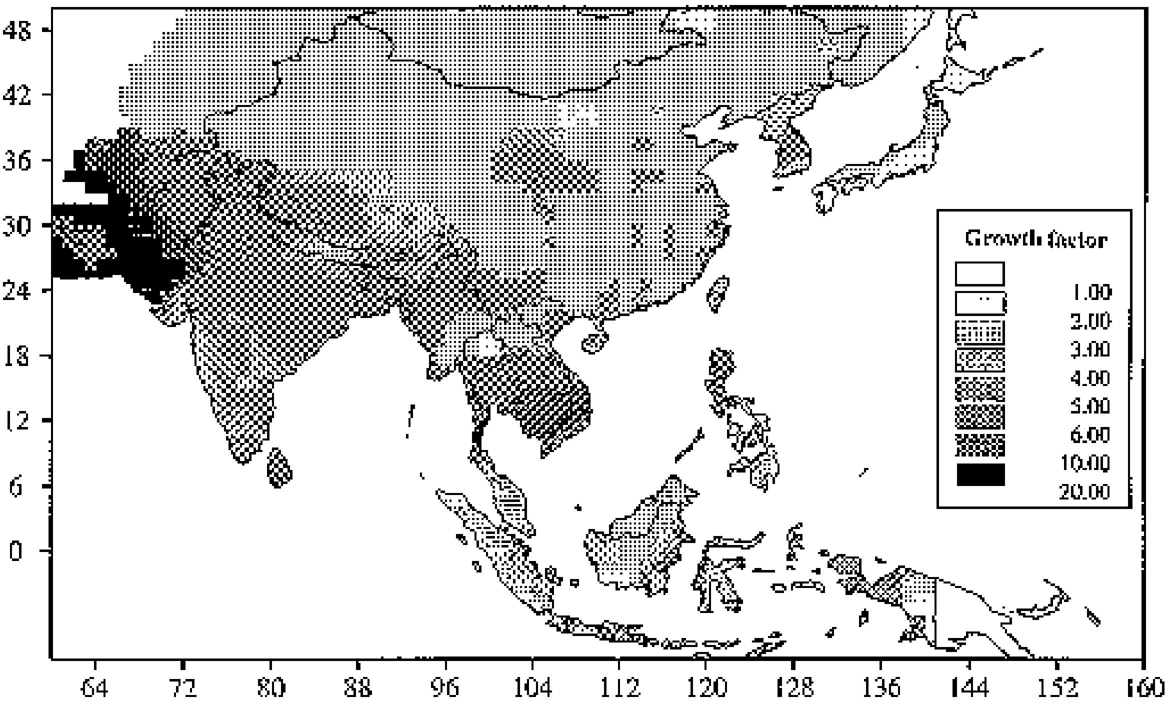

Figure 7.6 Growth in sulfur deposition between 1990 and 2020, Reference scenario (base case energy pathway, no further emission control measures current legislation assumed)

7.3.2 Achievement of critical loads for acid deposition

One way to judge the potential environmental damage caused by increased sulfur deposition is to compare deposition with critical loads, which resemble the maximum deposition that will not cause chemical changes leading to harmful effects on ecosystem structure and function. A detailed description of how critical loads have been estimated and how excess deposition can be interpreted is provided in Chapter 6 of this report. Figure 7.7 displays excess deposition, i.e., sulfur deposition above the critical loads, for the reference scenario for the year 2020. As a conservative assumption the 25 percentile of critical loads database has been used for this analysis, allowing for eventual uncertainties and data inaccuracies in the quantitative estimates of the critical loads.

Figure 7.7 shows that under the reference emission scenario, i.e., in the do-nothing case, critical loads will be exceeded in many regions in Asia, although not everywhere. Pakistan, the western and central parts of India, western China, Myanmar and parts of Indonesia experience no or only little excess deposition even under the highest emission scenarios considered in this paper. In other areas, e.g., in southern and eastern China, in Korea and in northern Thailand, widespread serious excess deposition has to be expected. In addition, many 'hot spots' occur on the local scale.

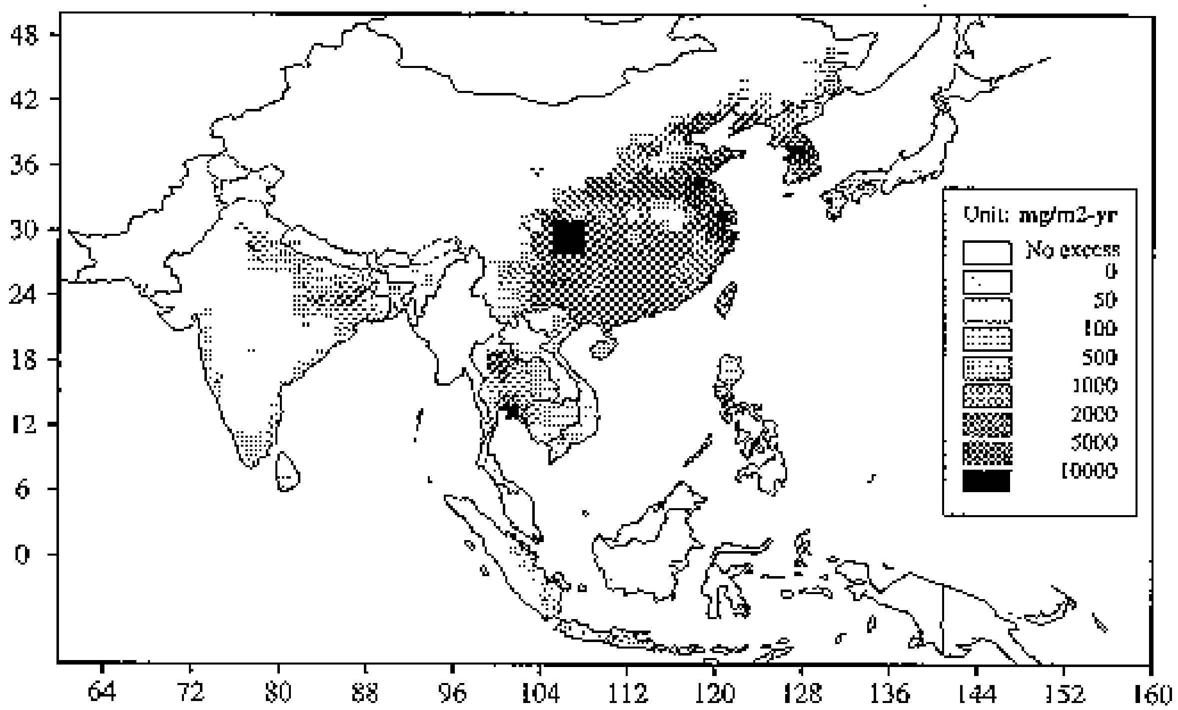

Figure 7.7 Excess deposition above critical loads (all ecosystems) in 2020, Reference scenario (no further emission control beyond current legislation assumed).

It must be emphasized that - under the assumptions of this scenario - excess deposition will reach unprecedented levels in some regions: The RAINS model calculates that critical loads will be exceeded by between two and five grams sulfur per square meter per year in large parts in central and eastern China, in northern Thailand. Highest excess deposition (up to 15 to 20 grams sulfur per square meter per year) is calculated for some ecosystems in Korea, the Bangkok metropolitan region, and in the Sichuan and Shanghai provinces. For comparison, total sulfur deposition in many of these areas is currently in the range of two to three grams.

Although the current state of scientific knowledge does not yet allow drawing conclusions about the environmental damage implied with such excess deposition, the fact that sulfur deposition will be more than ten times above the sustainable levels in large areas may give reason for serious concern. To derive more specific information on potential environmental threats, the RAINS model enables the examination of conditions for various types of ecosystems individually. To illustrate this feature, Figure 7.8 displays excess deposition only for agricultural ecosystems. Calculations show that the growth of sulfur deposition could have a severe negative influence on the conditions of many important agricultural crops in Asia. The fact that the major rice growing areas in Asia (e.g., in China, India and Japan) will experience excess deposition up to 15 grams per square meter and year may also give reason for serious concern.

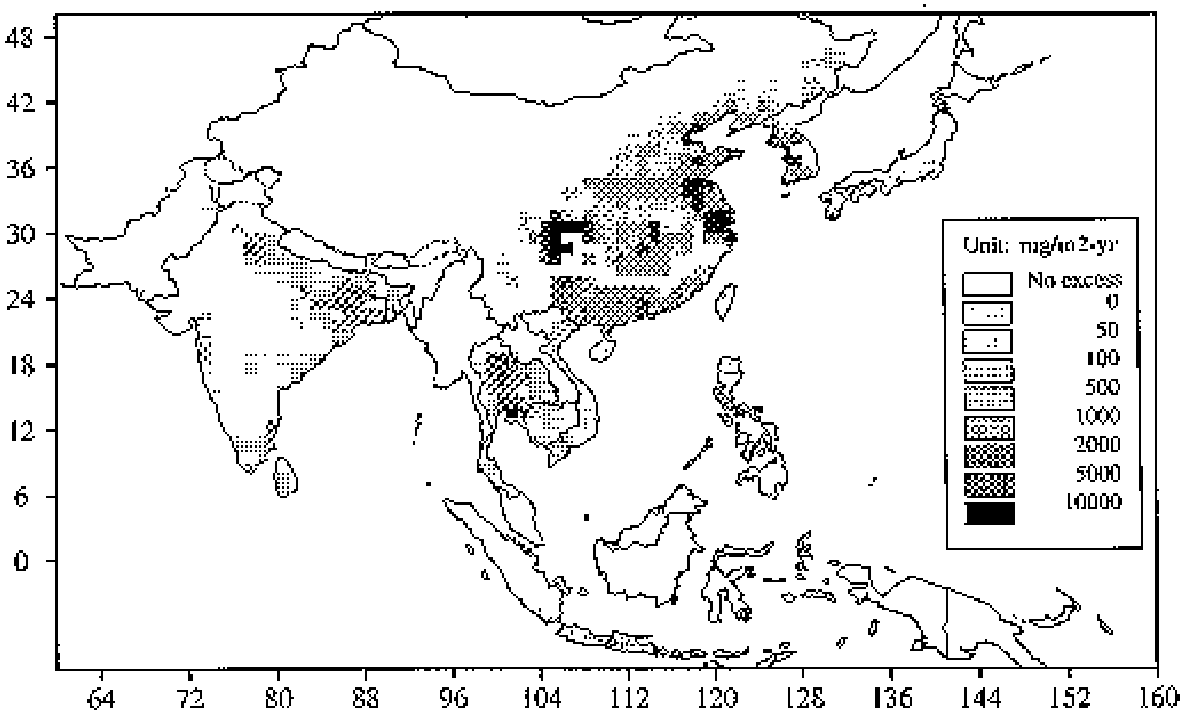

Figure 7.8 Excess deposition above critical loads for agricultural ecosystems in 2020, Reference scenario (no further emission control beyond current legislation assumed).

Obviously, deposition of air pollutants influencing the soil chemistry represents only one potential cause for environmental damage. Analysis shows, however, that high deposition is always linked to sufficiently high levels of ambient concentrations. The associated ambient SO_2 levels in the rice growing regions in China are estimated to reach in this scenario up to 60 micrograms SO_2/m^3 (Figure 7.9). Although specific analysis of dose-response relationships for rice paddies is still lacking, a rough extrapolation of the threshold levels for similar ecosystems (which range usually from 20 to 30 micrograms/m^3, see e.g. IUFRO, 1978) would suggest an excess of these levels by a factor of two to three.

High ambient levels of SO_2 concentrations resulting from this scenario do not only imply serious risks to natural and agricultural ecosystems, but impose also serious threat to human health. One of the first and most visible signals is the deterioration of urban air quality in large metropolitan agglomerations in Asia. Although the assessment of urban air pollution was excluded from the first phase of the RAINS-Asia work, Figure 7.9 suggests the unabated scenario to exceed the WHO guideline of 40-60 micrograms SO_2/m^3 (annual average - WHO, 1979) in many Asian regions, even calculated as an average over grids with a size of one degree longitude by one degree latitude resolution. Although a direct link to actual air quality in cities is not yet possible, experience shows that actual concentrations in the urban centers of a grid are usually substantially higher than the grid average. Calculated on the same spatial resolution the model shows that ambient levels of SO_2 concentrations increase in many regions in Asia by a factor of four to five compared to the 1990 levels.

As outlined above it can be expected that the growth in SO_2 emissions associated with the envisaged evolution of energy use gives reason for serious concern about maintaining sustainable conditions for natural and agricultural ecosystems in Asia. Sulfur deposition will cause significant changes in the soil chemistry over wide areas in Asia, affecting growing conditions for many natural ecosystems and agricultural crops. Ambient levels of SO_2 will exceed WHO health guidelines not only in cities, but also in many rural regions. If no countermeasures were taken, a degradation of the environmental quality to unprecedented levels has to be anticipated.

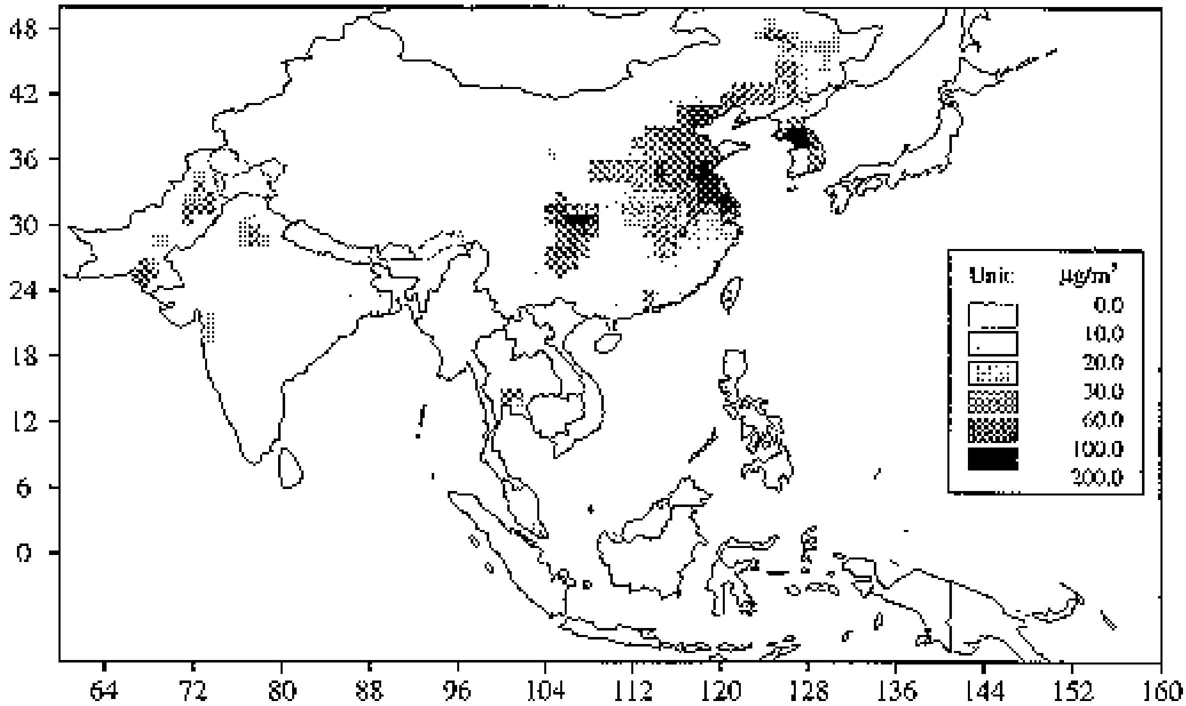

Figure 7.9 Ambient levels of SO_2 concentrations in Asia, 2020, reference scenario (no emission control beyond current legislation assumed)

A major feature of the RAINS model is its capability to simulate SO_2 emission control strategies and explore their costs and their regional environmental benefits in physical terms. In the model, emissions can be reduced by prescribing specific measures at selected sources, i.e., at specific economic sectors in individual regions or countries. Details of how emission control measures and costs have been modelled in RAINS are provided in Chapter 4 of this report.

In response to the finding of the previous section, i.e., that realizing the officially anticipated energy development without any measures to control emissions might cause dramatic negative environmental impacts, the following sections explores costs and environmental benefits of alternative strategies for reducing SO_2 emissions. Sections 7.4 and 7.5 discuss the impacts of applying certain packages of emission control measures throughout the region. Thereafter, Sections 7.6 to 7.8 explore the potential for cost savings offered by selective application of technologies guided by the different levels of environmental sensitivities.

7.4 Exploring the technical potential for reducing SO_2 emissions: The BAT (Best Available Technology) scenario

To explore the potential, costs and ecological improvements offered by advanced technological means to reduce emissions a scenario has been developed which simulates for the base case energy pathway the application of advanced emission control technologies to all relevant emission sources throughout Asia. The measures considered in this scenario represent the current technological standards in many industrialized countries. In particular, wet flue gas desulfurization (WFGD) processes are assumed for all industrial and power plant boilers burning coal and oil, including retrofits of the existing boiler stock. Since, for obvious technical reasons, in the residential/commercial (domestic) sector and in the transport sector the use of flue gas desulfurization is not possible, the use of low sulfur fuels (low sulfur coal, low sulfur oil) has been assumed for all small sources (Box 1).

Box 1: Measures assumed for the 'best available technology' (BAT) scenario

The Best Available Technology (BAT)-scenario

- Flue gas desulfurization (wet limestone scrubbing) for all (existing and new) large power stations (LPS) burning coal and oil
- Flue gas desulfurization (wet limestone scrubbing) for all large industrial boilers
- Use of low sulfur fuels (coal, heavy fuel oil, gasoil) for all other users

The RAINS model shows that advanced emission control methods applied to the fuel consumption levels as suggested by the reference energy scenario could drastically reduce SO_2 emissions in Asia below the current levels. Between 1990 and 2020, SO_2 emissions from the region would decline from 33.6 to 16.3 million tons, i.e., by 51 percent, despite the assumed growth in energy consumption by 230 percent. Since control technologies work most effectively at large sources, the relative contribution from large point sources declines from 16 percent in 1990 to less than nine percent in 2020. Note, that this is much in contrast to the unabated scenario, in which the share of large point sources increases to 25 percent.

Different structural compositions in the emission sources create also a wide span in the evolution of national emissions. For instance, as a result of such a policy, emissions from China, the Philippines and Thailand would decline by 60 to 70 percent, whereas India's emissions would still increase by about one third compared to 1990 (Table 7.1).

Not surprisingly, declining emissions will also result in reduced sulfur deposition. Most interesting, however, is a comparison between the diminished deposition and the critical loads. As displayed in Figure 7.10, a general use of advanced emission control technologies will bring down sulfur deposition below the critical loads almost everywhere in the regions. A major exception is the border area between the Hunan and Jiangxi provinces in China, where sensitive ecosystems are located in regions with intense economic activity. Additional isolated 'hot spots' occur in India, Thailand and Korea.

The scenario shows that, despite the more than three-fold increase in energy consumption expected for the next few decades, sustainable conditions - at least in terms of sulfur deposition - could be achieved by advanced technologies for most of the Asian ecosystems.

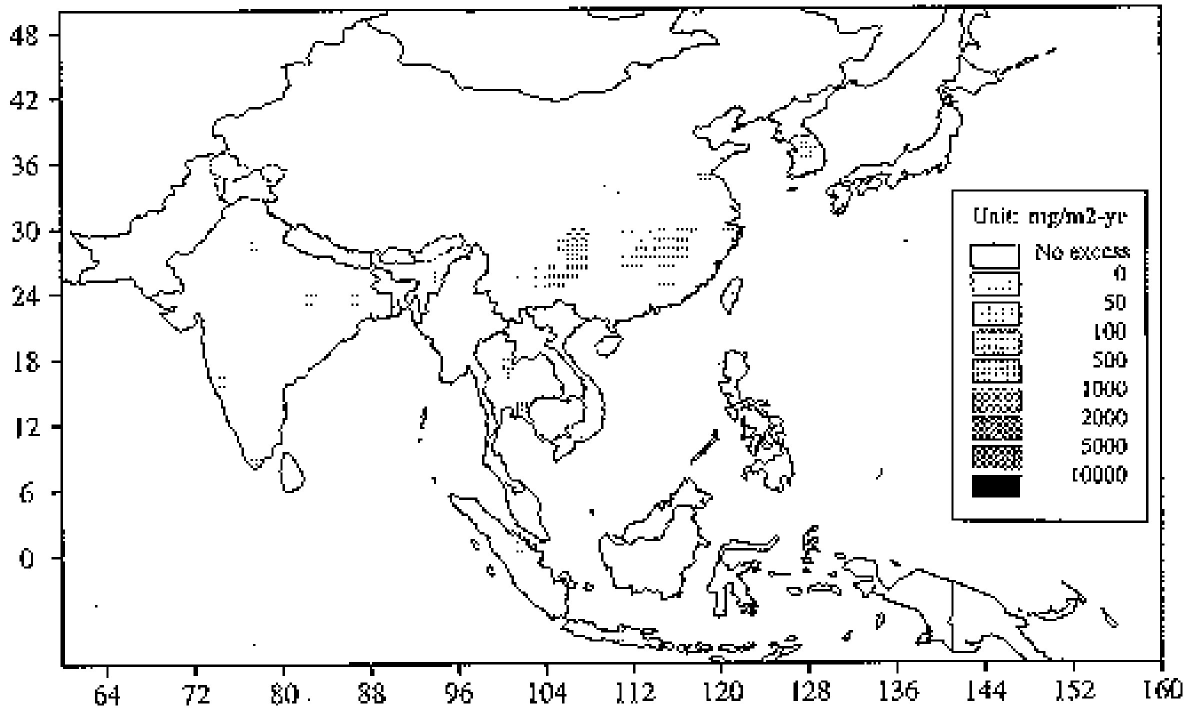

Figure 7.10 Excess of critical loads for the BAT scenario in 2020

The success in ecosystem's protection achievable with advanced control technologies, however, has its price. The RAINS model also enables analysis of the costs involved in various emission control technologies. As discussed in Chapter 4, the cost evaluation of the RAINS model has been restricted to the incremental costs caused by emission control measures and does not include the total costs of the energy system. Furthermore, as outlined before, cost estimates reflect annualized full life cycle costs (including investments and operating costs).

In the year 2020 full application of advanced emission control technologies would require 90 billion US $ per year, which is about 0.59 percent of the regional GDP assumed for the underlying energy scenario. For comparison, the relative costs for the latest agreement on reducing sulfur emissions in Europe (the Oslo protocol) were only about one third of this level (0.21 percent of the GDP; Amann *et al.*, 1994). It should be pointed out that there exists a wide range in burdens to the various national economies: Whereas for some countries with low consumption of fossil fuels (e.g., Myanmar) or highly developed economies (e.g., Japan) the abatement costs are comparably low (0.05 and 0.06 percent, respectively), developing countries with a heavy reliance on coal face substantially higher burdens (e.g., China, 1.7 percent). In Europe, the highest share of GDP for the latest agreement was 0.79 percent.

Since the environmental benefits of such a strategy cannot yet be quantified in monetary terms, a definite answer about the cost-benefit ratio of fully applying western emission control standards cannot be derived yet. It has to be observed, however, that the costs associated with such a strategy would put significant burdens on many developing economies in the region. Consequently, the following sections use the RAINS model to search for alternative, perhaps more cost-effective, solutions to reduce source emissions in Asia.

7.5 An advanced emission control technology (ACT) scenario

Section 7.4 has explored a scenario that applies best available emission control technologies to all emission sources in Asia. As a consequence, emissions would be greatly reduced, resulting in a fall in sulfur deposition levels below the critical loads for most of Asia. An obvious option for cost-savings would be to reduce the overachievement of the critical loads by selecting only the most cost-effective measures to reduce emissions. If structural changes in the energy system, such as energy conservation measures and fuel substitution, are left aside for a moment, the remaining technologies show a wide range of cost-effectiveness, i.e., they reduce different amounts of sulfur for the same amount of money (Table 7.2). A rational policy could therefore request only the most cost-effective measures, thereby reducing the achieved emission reductions to some degree, but to a greater extent also the involved costs.

To follow this idea further, a scenario has been developed which assumes the application of advanced control technologies (wet flue gas desulfurization WFGD) only for new, large emission sources in the power plant, the industrial and refinery sectors. Emissions from existing power stations and from small sources in the industry are assumed to be controlled through the use of low sulfur fuels[1] (50 percent share of low sulfur coal and oil). Also in the domestic and transport sectors low sulfur fuels are prescribed (see Box 2). For Japan and Taiwan, however, the scenario assumes compliance with current national legislation.

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[1] For gasoil the limit adopted in the ACT strategy is 0.3 percent. Limits for other fuels are as for the BAT strategy.

Box 2: Measures for the advanced emission control scenario

The Advanced Control Technology (ACT)-scenario

- Flue gas desulfurization (wet limestone scrubbing) for all new power stations
- Flue gas desulfurization (wet limestone scrubbing) for all large industrial boilers in refineries
- Low sulfur fuels for boilers in industry (100% of liquid fuels and 50% of coal consumption)
- Low sulfur fuels for the domestic and transport sectors (100% of total consumption)

As expected, restricting advanced measures to certain sources lowers the emission reductions. Whereas the BAT strategy will be able to cut total SO_2 emissions in Asia by half up to 2020, the ACT scenario produces a 50 percent increase of emissions at a level of 50.4 million tons. However, this level is still less than half of the unabated level of 110 million tons.

Selecting only the most cost-effective measures cuts down costs. From more than 90 billion US $/year (costs for the BAT scenario in 2020) costs drop to 39 billion US $/year, i.e., by about 57 percent. Consequently, compared to GDP the strategy would only take a share of 0.25 percent, which is already close to the 0.21 percent level currently discussed in Europe.

It has been pointed out earlier that, due to country-specific structural differences, the actual situation varies considerably among countries. In China, where the BAT strategy would consume 1.7 percent of GDP, limiting measures to the more cost-effective technologies will reduce the share to 0.59 percent of the GDP. Thereby, the burden is comparable to other countries such as India, Indonesia, the Philippines and Thailand, which all are in a range between 0.51 to 0.57 percent of GDP.

Table 7.2 Cost-effectiveness of available measures for area sources in the North Highlands region in Thailand

Fuel	Sector	Control technology	Cost, US \$/ton SO_2 removed	
			Unit costs	Marginal costs
Brown coal	Power plants	WFGD	208	208
Heavy fuel oil	Power plants	WFGD	403	403
Heavy fuel oil	Conversion Industry	WFGD	468	468
Brown coal	Industry	WFGD	689	689
Heavy fuel oil	Domestic Transport	LSHF	1084	1084
Gasoil	All sectors	LSMD1	1823	1823
Hard coal	Industry	WFGD	2710	2710
Brown coal	Power plant	RFGD	287	2792
Heavy fuel oil	Power Plant	RFGD	732	11150
Gasoil	All sectors	LSMD2	5469	15677
Heavy fuel oil	Industry Conversion	RFGD	997	17742
Brown coal	Industry	RFGD	1565	29311
Hard coal	Industry	RFGD	6720	133729

Legend:

Control technologies:	WFGD - Wet flue gas desulfurization
	RFGD - Regenerative flue gas desulfurization
	LSHF - Low sulfur heavy fuel oil
	LSMD1, LSMD2 - Low sulfur medium distillates (0.3% S and 0.05% S respectively)

Unit cost shows the average cost of reducing one ton of SO_2 if a given technology is applied from the unabated case. Marginal cost shows the incremental cost of reducing additional ton of SO_2 if technologies are applied according to their cost - effectiveness.

Of course, reduced costs are accompanied by higher emissions. For instance in China, the ACT strategy results in a 37 percent increase of SO_2 compared to a 70 percent decrease of the BAT scenario.

Obviously, the ACT strategy reduces emissions at lower costs than a BAT scenario. To judge the environmental effectiveness, however, a comparison of the resulting deposition patterns with the critical loads is necessary. Figure 7.11 shows that areas with serious excess deposition occur in the ACT strategy in Korea and some Chinese provinces, whereas in most other regions the critical loads could be achieved.

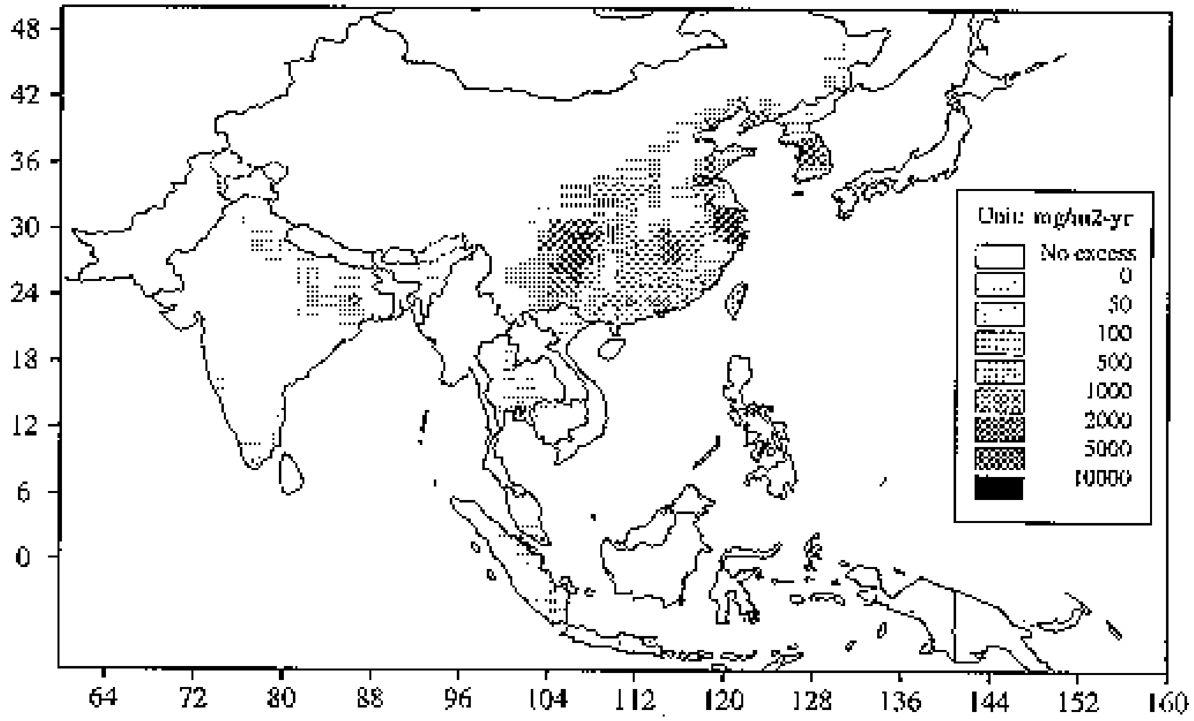

Figure 7.11 Excess deposition for the ACT strategy in the year 2020

7.6 A ’basic control technology’ (BCT) scenario

Although emission control costs are reduced significantly in the ’advanced control technology’ (ACT) scenario, the construction of such emission control devices according to world standards requires substantial technical know-how and capital investments. Experience shows that developing countries often have limited access to the necessary technical and financial resources needed to implement advanced technological solutions. Consequently, preference is often given to less advanced approaches readily available on the domestic market, which are also often less capital intensive.

To explore the economic and ecological features of strategies that give preference to domestic technologies an example scenario was constructed, in which use is made of domestically available control technologies. Therefore, instead of installing standard flue gas desulfurization units at large power stations, emissions from these sources would be controlled through more basic technologies with low capital requirements. As an example for such technical solutions, the RAINS model considers the lime stone injection process, which achieves emission reductions of about 50 percent. Investment requirements are low but, due to the significant amount of waste material to be handled, operating costs may be higher than for the standard flue gas desulfurization method.

The 'basic control technology' (BCT) scenario assumes that in China, India and Pakistan emissions from new large point sources are controlled by domestic technology (with a typical removal efficiency of about 50 percent) rather than by advanced flue gas cleaning methods (with efficiencies of more than 90 percent). For small sources in the industrial and domestic sector the use of low sulfur fuels is assumed (Box 3).

Due to the application of less efficient control technologies, the remaining emissions in all three countries will be higher than in the advanced technology scenario. For China, SO_2 emissions in the year 2020 would amount to 38.1 million tons (i.e., an increase of 77 percent), for India 13 million tons (+190 percent) and for Pakistan 3.6 million tons (+490 percent). In the ACT scenario comparable growth rates are 37 percent in China, 135 percent in India and 210 percent in Pakistan, respectively.

Box 3: Measures assumed for the basic technology scenario

The Basic Control Technology (BCT) - scenario

- China, India and Pakistan:
    - Domestic technologies with low capital requirements (e.g., lime stone injection) for all new coal fired power stations
    - Use of low sulfur fuels as in the ACT (Advanced Controls) scenario for the industrial and domestic sector

- All other countries:
    - Controls as in the ACT scenario

Most interesting, however, is the fact that total costs are close to the levels of the ACT scenario. This can be explained by the fact that the RAINS model calculates and compares total life cycle costs of emission control equipment: in the case of the currently used domestic control technologies the lower investments are compensated by higher operating costs, in particular for the treatment and disposal of waste material. Obviously, costs for waste disposal are strongly influenced by local conditions and legislation. Therefore, the RAINS model can only provide generic estimates of such costs, which in fact reflects the situation in developed countries. Lower legal standards for waste disposal facilities may reduce the costs considerably, however at higher environmental hazards caused by the deposits. To avoid a transfer of the air pollution problem to other media, such as a contamination of soils and ground water, the RAINS model bases its cost estimates on standards which strive to minimize such risks.

Figure 7.12 shows excess deposition for the basic technology scenario. Compared to the ACT scenario the increase in emissions from the large point sources results in a situation whereby many parts of eastern China face excess deposition of more than two grams per square meter and year, with peak exceedances in the Sichuan and Shanghai provinces of about ten grams. Consequently, it can be concluded that in the long run a strategy relying solely on control technologies with modest removal efficiencies will not be able to preserve important agricultural areas from serious excess deposition.

Table 7.3 summarizes emissions and costs from the three emission control scenarios discussed up to now. Obviously, there is a clear trade-off between emission levels, control costs and ecosystem’s protection.

Table 7.3 Emissions and control costs for the BAT, ACT and BCT scenarios in the year 2020

Country	SO_2 Emissions (thousand tons of SO_2)			SO_2 Control Costs (million US $/yr)		
	BAT	ACT	BCT	BAT	ACT	BCT
Bangladesh	165	258	258	475	228	228
Bhutan	3	4	4	7	9	9
Brunei	15	17	17	15	2	2
Cambodia	22	69	69	487	123	123
China	6672	29932	38124	34230	11975	12712
Hong Kong	24	68	68	574	255	255
India	5906	10522	13054	17055	6328	6213
Indonesia	438	785	785	6121	2255	2255
Japan	393	1047	1047	6132	3458	3458
Korea, north	75	7075	7075	3087	1089	1089
Korea, south	552	1469	1469	3769	3214	3214
Laos	5	7	7	9	6	6
Malaysia	66	246	246	843	163	163
Mongolia	13	81	81	138	56	56
Myanmar	32	37	37	32	5	5
Nepal	218	230	230	53	12	12
Pakistan	606	1907	3609	4333	3095	3703
Philippines	146	440	440	1201	1063	1063
Sea lanes	102	307	307	445	222	222
Singapore	65	221	221	860	635	635
Sri Lanka	37	53	53	222	173	173
Taiwan	245	827	827	2999	1249	1249
Thailand	336	813	813	6485	2916	2916
Vietnam	183	345	345	853	338	338
TOTAL	16321	50396	62822	90424	38877	40108

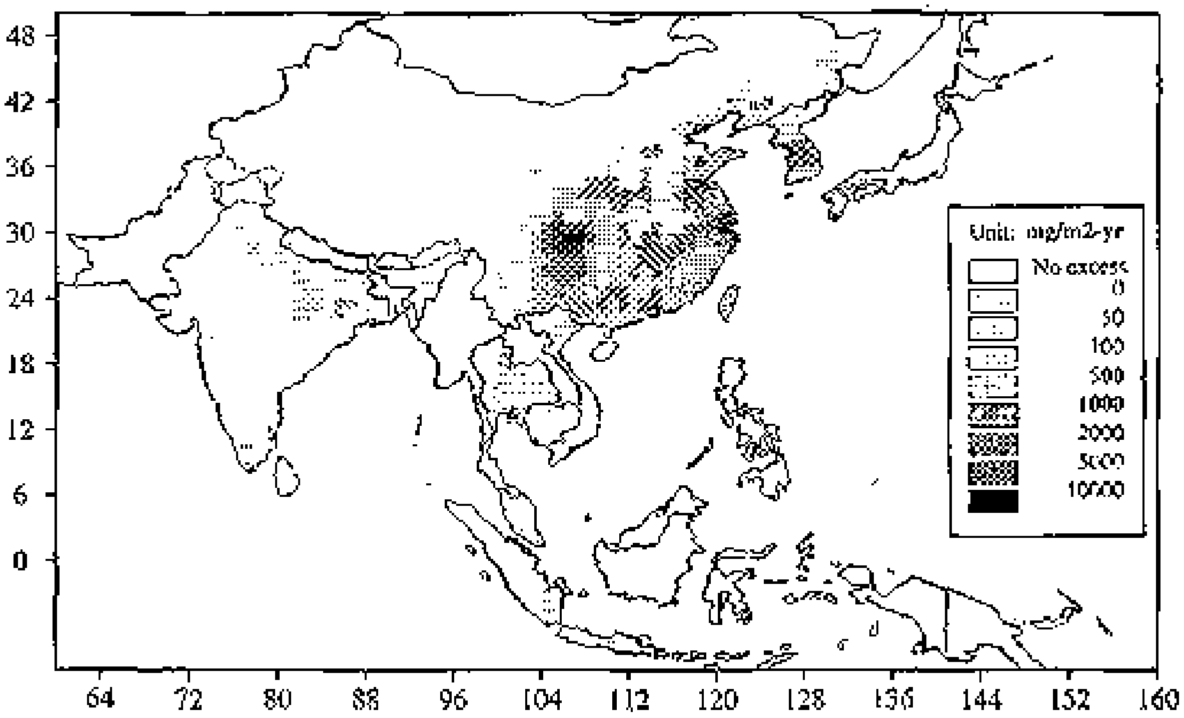

Figure 7.12 Excess sulfur deposition for the basic control technology (BCT) scenario for the year 2020

7.7 A scenario with local applications of advanced technologies (LACT)

The analyses carried out in the preceding sections shows that there is a clear trade-off between ecosystem protection and emission control costs. Furthermore, it became clear that different strategies have different cost-effectiveness, i.e., some of them achieve different protection levels for similar costs. The important question arises of how the cost-effectiveness of strategies could be further increased.

Ultimately, the integrated assessment process enables the optimization of emission control measures, e.g., in order to minimize costs for achieving exogenously specified target deposition or ecosystems protection levels. Earlier versions of the RAINS model implemented for Europe contain such optimization procedures and have been used to identify optimized abatement scenarios as a starting point for international negotiations (Amann *et al.*, 1993).

Although the present implementation of the RAINS model for Asia does not provide this capability, the model can already be used to search for cost-effective strategies. Section 7.4 (the advanced control technology scenario) made a step towards increasing cost-effectiveness in comparison to the best available technology (BAT) scenario by selecting only the most effective measures. A further reduction of costs, without increasing environmental damage, could be achieved by directing advanced control measures to ecologically sensitive areas and relaxing control requirements at less sensitive locations. It should be mentioned that China is currently exploring similar approaches by requesting only power stations in ecologically sensitive regions to reduce emissions (rational siting of plants, Zhao *et al.*, 1995).

As an illustrative example, a scenario is constructed for China, India and Pakistan that applies advanced emission control measures to only those provinces where significant excess deposition would occur without such measures (compare Box 4). Emissions and control costs for these three countries in the LACT scenario are shown in Table 7.4. In this scenario the emissions from low-income countries (e.g., Bangladesh, Cambodia or Sri Lanka) remain uncontrolled. Countries with higher per capita income (e.g., Indonesia, Japan, South Korea or Thailand) control their emissions as in the ACT scenario.

Table 7.4 Emissions and control costs in 2020 for China, India and Pakistan in the LACT scenario

Country	Emissions (thousand tons SO_2)			Costs, million US $		
	LACT	BCT	ACT	LACT	BCT	ACT
China	37904	38124	29932	8505	12609	12063
India	13434	13054	10522	3870	6214	6386
Pakistan	5592	3609	1908	857	3702	3102
Sum	56930	54787	42362	13232	22535	21551

Box 4: Regional emission control strategies for the Local ACT scenario in China, India and Pakistan

NO CONTROL	ADVANCED EMISSION CONTROL (ACT)
China:	
Fujian	Beijing
Guandong-Hainan	Chongquing
Guanxi	Guangzhou
Hebei-Anhui-Henah	Guyang
Inner Mongolia	Guizhou
North-eastern plain, Heilongjiang	Hubei
Shenyang	Hunan
West Tibet-Quinghai	Jiangsu
Yunnan	Jianxi
	Shanghai
	Shaanxi-Gansu
	Shandong
	Shanxi
	Sichuan
	Taiyuan
	Tianjin
	Wuhan
	Zhejiang
India	
Andra Pradesh	West Bengal
Bombay	Bihar
Karnataka-Goa	Calcutta
Kerala	Delhi
Madras	Eastern Himalaya-Assam
Maharasthra-Dadra-Nagar	Guijarat
Punjab-Chandigarh	Haryana
Western Himalaya-Jammu-Kashmir	Madhya Pradesh
	Orissa
	Tamil Nadu-Pondicherry
	Uttar Pradesh
Pakistan	
Lahore	Karachi
North-western frontier provinces	
Punjab	
Sind	

From Table 7.4 it can be derived that focusing advanced emission control measures on ecologically sensitive regions would result, for China and India, in emissions roughly comparable to the basic technology case, however, at only two thirds of the costs. Avoiding expensive - and environmentally less effective - controls in a group of low-income countries would save about 3 billion US $ in the year 2020.

As shown before in Figure 7.11, the ACT scenario reduces excess sulfur deposition in large areas of Asia, i.e., ecosystems would not be under threat. In the LACT case, ecosystems protection is slightly lower than in the ACT scenario, while costs decline substantially (Figure 7.13).

The scenario demonstrates that targeting emission control measures could substantially increase the cost-effectiveness of strategies. Taking China as an example, focusing measures to the ecologically sensitive regions could achieve environmental impacts roughly comparable to the Basic Control Technology (BCT) case while costs declining to 0.41 percent of GDP.

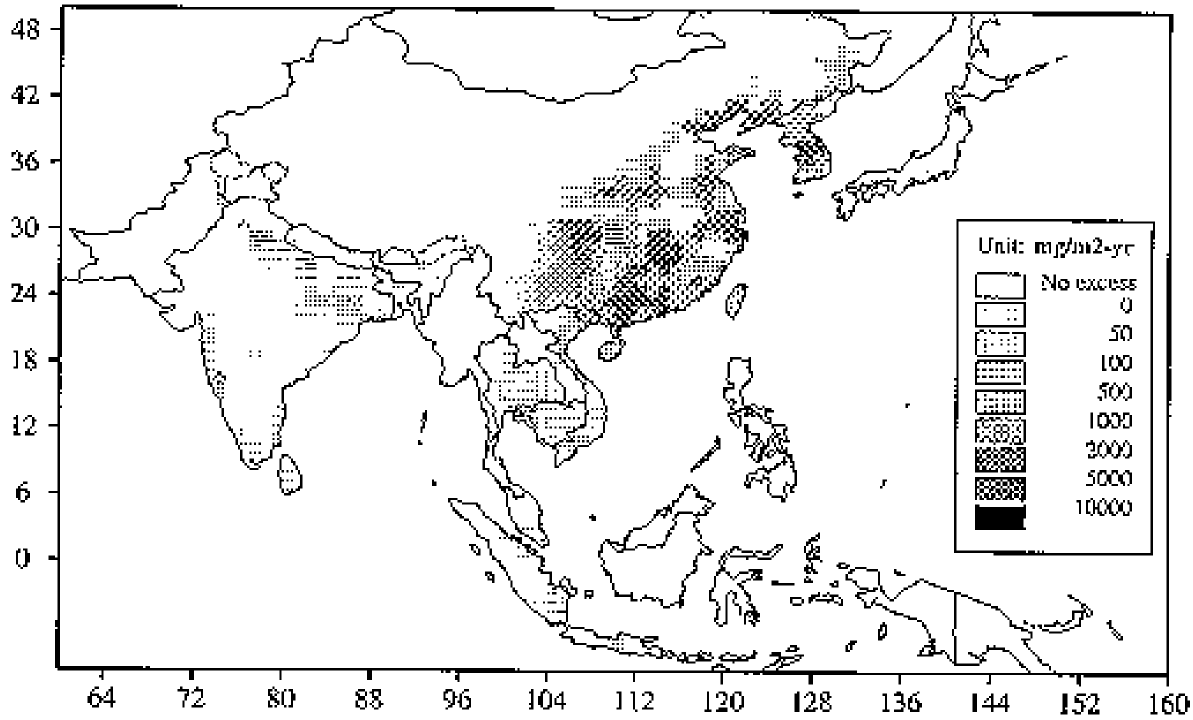

Figure 7.13 Excess sulfur deposition for the LACT scenario (local application of advanced control technologies) for the year 2020

7.8 Relocation of plants in sensitive regions

An alternative approach to protect sensitive ecosystems - or to avoid the occurrence of 'hot spots', i.e., areas with peak excess deposition - would be to locate new power stations in less sensitive regions. The RAINS model facilitates the analysis necessary for such strategies in various ways:

- The DEPOSITION module of RAINS provides an easy option to explore the dispersion of pollutants for each individual emission source considered in the model, i.e., the spread of emissions could be displayed for each of the 94 area sources and the 355 large point sources separately. Thereby, it is possible to identify whether a specific source has strong impacts on sensitive ecosystems.

- The DEPOSITION module of RAINS also enables the identification of the sources contributing to the deposition at a specific location.

- By using the energy module RESGEN the user can create new energy scenarios with a different regional allocation of newly built power station capacities, while maintaining the internal consistencies of the regional energy balances.

- To enable fast exploration of the environmental impacts of re-located power stations, the DEPOSITION module of RAINS offers the option to change the location of individual power stations without performing consistency checks on the energy balances.

This section provides examples of model use, aimed at a re-location of power stations with strong impacts on sensitive ecosystems to less sensitive regions. Excess deposition of the reference scenario (base case energy pathway, no further emission control beyond current legislation, year 2020) has been shown in Figure 7.7. 'Hot spots', with exceedance of critical loads of more than ten grams sulfur/m^2/year occur, inter alia, in the Chinese Sichuan province and in the central and northern part of Thailand. Table 7.5 lists the contributions to deposition in the year 2020 for two grids, based on the RAINS calculations.

Table 7.5 shows that some point sources make a significant, and often dominant, contribution to local deposition (e.g., the Chengdu power station contributes about 30 percent of total deposition to grid 105/30). Consequently, measures that focus on a few specific sources could significantly improve the local situation. However, emissions do not only have a local impact, but are dispersed via the atmosphere to a larger area. To explore this feature, the RAINS model has been used to create Figure 7.14, displaying the spread of emissions and the resulting deposition from the Lampang power station expected for the year 2020 under the reference scenario.

Table 7.5 Contribution of sulfur deposition to two grids for the reference scenario for the year 2020 in milligrams sulfur/m^2/year (note that some of the power stations are only foreseen for the year 2020 and do not yet exist!)

Grid 105/30 (Sichuan)		**Grid 100/18 (Northern Thailand)**	
Area sources:			
China, Sichuan	10324	Thailand, Northern Highlands	1047
China, Chongquing	1085	Thailand, Bangkok	18
China, Yunnan	115	Thailand, other area sources	14
China, Shaanxi-G.	47		
China, Guizhou	94	India (all sources)	15
China, Guiyang	28	China (all sources)	27
China, West Tibet	16	Bangladesh (all sources	3
China, Hubei	16	Other countries	3
China, Hebei	8		
China, Hunan	5		
China, Other Provinces	11		
India, all sources	6		
Large Point Sources			
China, LPS N25 (Chengdu)	5901	Thailand, LPS 1 (Lampang)	2696
China, LPS N24 (Jianqou)	993	Thailand LPS 2 (Mae Moh)	4231
China, LPS 56 (Baima)	189	Thailand, 2 other LPS	10
China, LPS 4 (Chongqing)	129		
China, LPS N1 (Luohang)	118		
China, LPS N65 (Douba)	89		
China, LPS N66 (Huayinshan)	65		
China, LPS N59 (Xigu)	13		
China, LPS 11 (Qinzhen)	13		
China, LPS N22 (Jingyuan)	11		
China, 10 other LPS	27		
TOTAL	**19303**	**TOTAL**	**8064**
Critical load (25 percentile)	4035	Critical load (25 percentile)	490

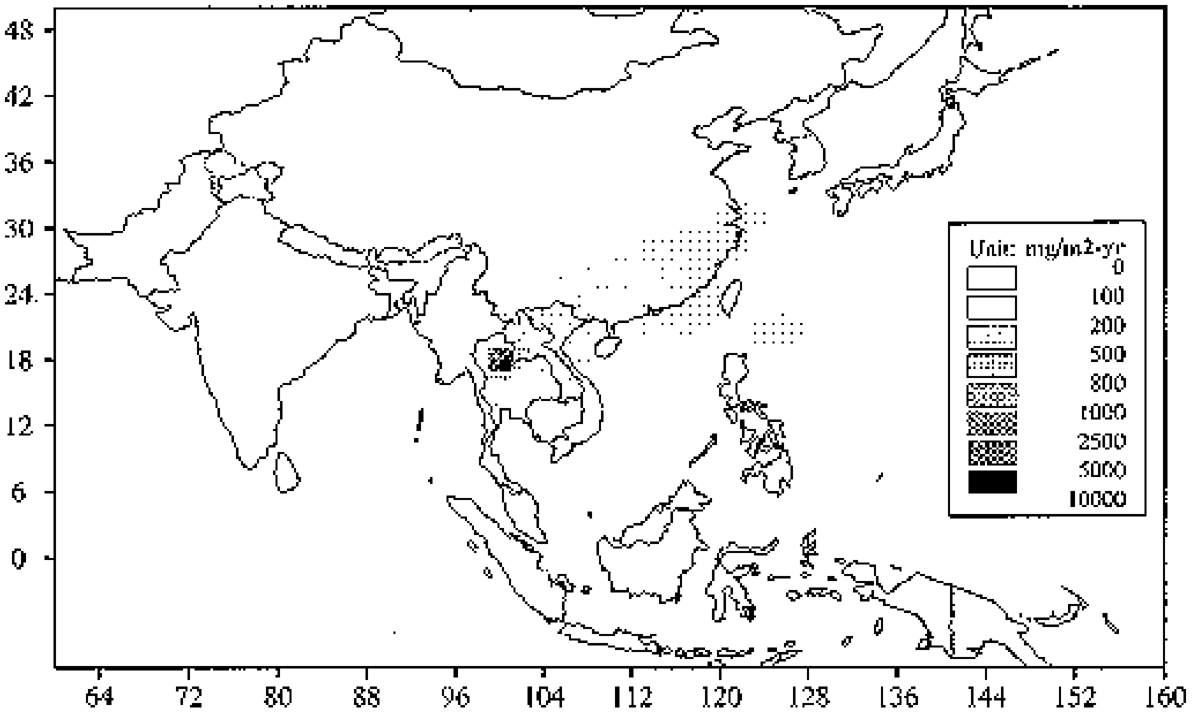

Figure 7.14 Sulfur deposition from the Lampang power station for the reference scenario (no emission control assumed) for the year 2020

The RAINS model could be used to explore the impact of reducing emissions at these power stations by introducing various emission control options. Another way to limit environmental impacts could be to move individual stations to less sensitive areas. To illustrate the capacity of the model, this scenario assumes that some coal power stations, which make significant contributions to excess deposition in sensitive ecosystems in the baseline scenario, are moved to less sensitive regions in the same country. Starting from the baseline scenario (no further emission control beyond current legislation) such moves have been assumed in China and Thailand (Box 5). In China, four sources planned for construction in the heavily polluted region of the Sichuan province have been moved to the northern part of the country. For Thailand, the scenario explores the effects of moving two large point sources from the north of the country to the southern peninsula. One of those sources has been simultaneously switched from lignite to imported hard coal. It should be stressed that this scenario only illustrates the capabilities of the RAINS model: it does not suggest the technical, economic or political feasibility of such moves. To answer such questions, more detailed case studies on local energy supply, demand and power transmission options will be necessary.

Box 5: Relocations of power plants assumed in the scenario

	Emissions in 2020, thousand tons of SO_2	Location (long/lat)	
		before move	after move
China:			
Sichuan, LPS N24 (Jianqou)	330	104/31	106/39
Sichuan, LPS N25 (Chengdu)	406	104/30	109/40
Sichuan, LPS 56 (Baima)	469	105/29	112/39
Sichuan, LPS N65 (Douba)	333	104/28	113/40
Thailand:			
Centr. Valley, LPS 3 (Ao Phai)	542	100/13	98/8
North Highlands, LPS 1 (Lampang)	617	99/18	99/9

It is outside of the scope of the RAINS model to determine the costs of such modified expansion plans. The model can, however, explore the environmental improvements, in terms of critical loads achievement, of such measures. Even under the assumption that the relocated power stations would not be equipped with desulfurization technologies, excess deposition in the hot spots declines compared to the baseline reference scenario. For instance, in the Sichuan province in China excess deposition in the grids affected by the moved sources decreased by about five to six g/m^2-yr, whereas, due to the large tolerance of acid deposition of the ecosystems in the new locations, no major areas would experience excess deposition as a result of this measure (Figure 7.15). Environmental improvements also occur in Thailand, where excess deposition in the northern part declines by about 50 percent.

It should be stressed again that this scenario has only an illustrative character, since the necessary support studies on the site conditions of the energy supply systems have not been carried out.

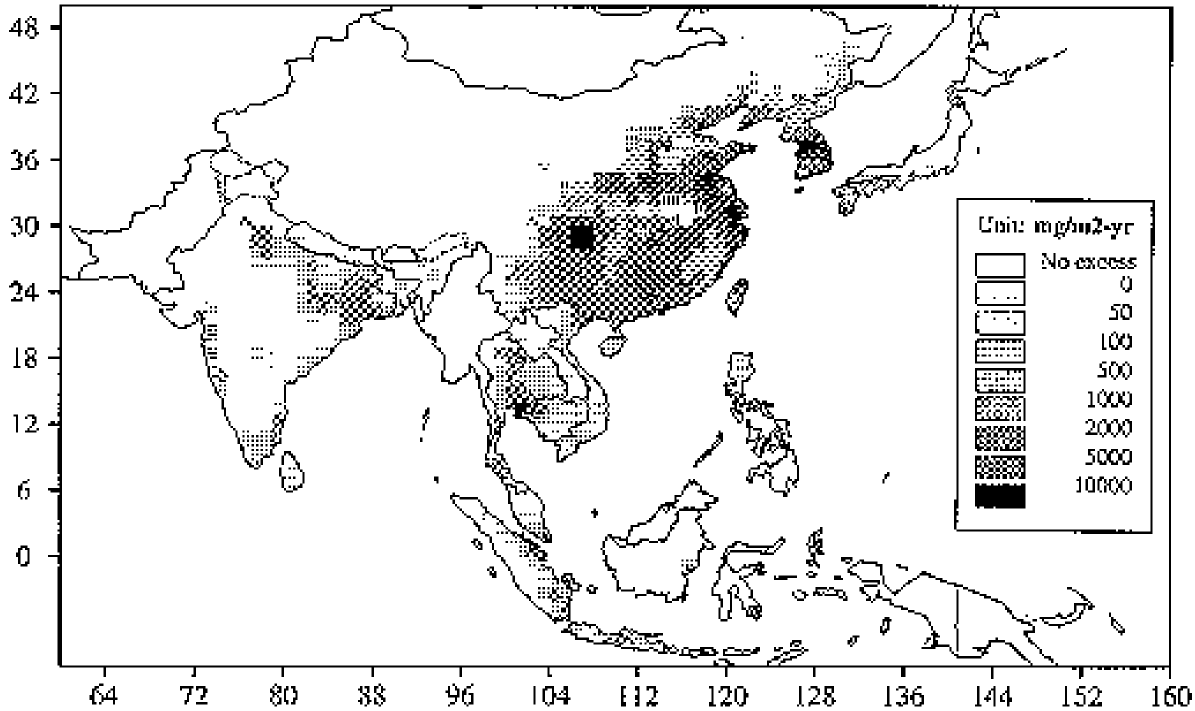

Figure 7.15 Excess sulfur deposition for a scenario in which some new power stations in China and Thailand are moved to ecologically less sensitive regions

7.9 Implications of the energy efficiency pathway

All the six scenarios discussed above are based on certain assumptions about the development of the economies and of energy intensities. As will be shown, however, the volumes and the structural composition of energy supply have a critical influence on the level of emissions. This means that not only will emission levels be crucially dependent on the energy scenario, but also that energy policies promoting energy efficiency and use of cleaner fuels are important instruments to reduce pollution and pollution control costs.

To illustrate this fact this section compares calculations for some of the emission control scenarios discussed above, which are all based on the reference energy pathway, with control strategies based on the energy efficiency pathway. Table 7.6 shows that, due to a lower consumption of fuels, SO_2 emissions in the energy efficiency pathway are consistently lower than in the base case energy path. Consequently, emission control strategies based on the energy efficiency pathway provide better protection for the ecosystems than would result from the base case.

Furthermore, the table shows that, despite the lower emission levels resulting from the various control scenarios, the costs for achieving the (lower) emissions are also about 30 percent below the costs of the base case energy pathway. Since, as has been pointed out in Chapter 3 of this report, both energy pathways are based on the same economic development assumptions (e.g., the growth of GDP), the energy efficiency pathway would also alleviate the burdens imposed by SO_2 control measures on the national economies. To carry the example case further, the cost of the abatement measures for the focused application of advanced control technologies (LACT) scenario based on the energy efficiency pathway in China, would amount to 0.29 percent of GDP instead of the 0.41 percent calculated for the base case. At the same time China would face less excess deposition than in the reference case.

Table 7.6 Comparison of emissions and emission control costs for the base case energy pathway and the energy efficiency pathway

		Emission control scenario			
	Energy pathway	**No Further Control (NFC)**	**Basic Control Technology (BCT)**	**Advanced Control Technology (ACT)**	**Best Available Technology (BAT)**
Emissions (million tons SO_2)	Base case	110.5	62.8	50.4	16.3
	Efficiency	80.1	47.1	39.1	12.4
Costs (billion US $/yr)	Base case	3.9	40.1	38.8	90.4
	Efficiency	2.0	26.9	25.5	65.6

7.10 Conclusions

If no countermeasures were taken, an initial analysis with the RAINS-Asia model indicates that currently observed trends in energy consumption will impose significant environmental threats to a variety of ecosystems in large parts of Asia. Within the next two to three decades, regional SO_2 emissions are expected to triple in Southeast Asia. In many areas, sulfur deposition will increase by more than a factor of five and exceed the levels observed in the most polluted areas in central and eastern Europe.

This increase in SO_2 emissions, which is strongly connected with the presently observed and expected future growth of economic activities and energy consumption, will severely threaten the sustainable basis of many natural and agricultural ecosystems in the region. Taking the critical loads estimated in this study as an indicator for sustainable levels of acid deposition, future sulfur deposition will exceed critical loads by more than a factor of ten in wide parts of Asia.

The exploratory analysis carried out for this study demonstrates that there is a variety of measures that can be taken to reduce SO_2 emissions and thereby avoid widespread excess deposition in the region. Advanced emission control technologies could reduce emissions below current levels even in a high growth energy scenario, albeit at extremely high costs. Illustrative scenarios demonstrate the potential for an increase in the cost-effectiveness of strategies if measures are focused on specific fuels, technologies, economic sectors, emission sources or ecologically sensitive regions.

The analysis shows that energy planning is also an important factor for controlling adverse environmental effects, in particular acidification. The development of carefully designed energy systems is of particular importance for controlling emissions in those countries considering an expansion or replacement of the present energy infrastructure.

RAINS-Asia is now available as a tool for the integrated assessment of strategies to keep SO_2 emissions from energy use at acceptable levels. The model enables the comparison of regional emissions, deposition and ecosystem protection levels resulting from different energy development pathways and from different emission control strategies. It simulates the effects of specific technologies and measures for a variety of fuel types and economic sectors, applicable to any of the 94 regions and 355 large point sources considered in the RAINS-Asia model. The model provides estimates of the emission control costs for each source, and assesses protection levels for up to 31 types of different ecosystems in Asia.

The analysis presented in this study has to be seen as an initial attempt to develop the necessary tools required for an integrated assessment of regional energy development that takes environmental impacts at different spatial and temporal scales into consideration. Although major progress towards this goal has been achieved, several aspects have to be further improved or added into the analysis. Special attention should be devoted to validation of the various models and databases developed in the first phase of the project. An important element currently missing is the development of the huge urban agglomerations in Southeast Asia, which may put severe pressure on local and regional air quality. Furthermore, refined methods of uncertainty and robustness analysis will have to be developed to assess the accuracy and reliability of model results.

References

Amann M., Klaassen G., Schoepp W., 1993: Closing the Gap Between the 1990 Deposition and the Critical Sulfur Deposition Values. Background Paper for the UN/ECE Task Force on Integrated Assessment Modelling, UN/ECE, Geneva, Switzerland.

IUFRO (International Union of Forest Research Organizations), 1978: Resolution über Maximale Immissionsraten zum Schutze der Wälder. Fachtagung Laibach/Jugoslawien 18 - 23 September 1978.

WHO (World Health Organization), 1979: Environmental Health Criteria 8 - Sulfur Dioxide. Geneva, Switzerland.

Zhao D., Mao J., Xiong J., Zhuang X., Yang J., 1995: Critical Load of Sulfur Deposition for Ecosystem and its Application in China. Research Center for Eco-Environmental Sciences, Academia Sinica, Beijing, China, pp.23.