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Journal of Environmental Management 72 (2004) 149–161

Journal of Environmental Management

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Cost-effective control of SO_2 emissions in Asia

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Received 8 March 2003; revised 23 March 2004; accepted 6 April 2004

Abstract

Despite recent efforts to limit the growth of SO_2 emissions in Asia, the negative environmental effects of sulphur emissions are likely to further increase in the future. This paper presents an extension of the RAINS-Asia integrated assessment model for acidification in Asia with an optimisation routine that can be used to identify cost-effective emission control strategies that achieve environmental targets for ambient SO_2 concentrations and sulphur deposition at least costs. Example scenarios developed with this optimisation module demonstrate a potential for significant cost savings in Asia, if emission controls are allocated to those sources that have the largest environmental impact and are cheapest to control. It is shown that strategies that simultaneously address harmful population exposure and the risk of vegetation damage from acid deposition result in the most cost-effective use of resources spent for emission controls.

Keywords: Integrated assessment; Sulphur emissions; Emission controls; Health and ecosystems effects; Cost-efficiency; Optimisation; Asia

1. Introduction

Sulphur is at the core of the most pressing air pollution problems in Asia: sulphur emissions cause urban pollution, they contribute to acid deposition and they influence climate change (Rodhe et al., 1992). Most of Asian sulphur emissions originate from coal combustion, which satisfies at present about 80% of the energy demand in the region. Primary energy demand has grown in Asia over the last 25 years at a pace twice as fast as the world average (Shah et al., 2000), and the demand for coal and oil is expected to further double or triple in the next 30 years. Thus Asian sulphur emissions, already now nearly equal to those from Europe and North America combined (Foell et al., 1995), are expected to continue to increase in the next decades (Klimont et al., 2001).

Sulphur emissions can be reduced through a wide variety of technical and non-technical measures. While many industrialised countries throughout the world have managed to substantially decrease their sulphur emissions over the last decades (Amann, 2001), developing countries in Asia have only taken first steps into this direction. The high financial burdens put on the developing economies in Asia by such emission control measures impeded a more rapid penetration of advanced emission controls. This paper shows that, based on scientific information, targeted emission control strategies can be designed that reduce the effects of sulphur emissions in much more cost-effective ways than traditional approaches.

The paper starts with a brief review of the recent development of sulphur emissions in Asia (Section 2), and proceeds by pinpointing a growing pressure on the control of SO_2 emissions in order to maintain—or revert to—acceptable levels of air quality (Section 3). It presents a methodology to optimally allocate emission controls to those sources that cause the largest environmental damage and that are cheapest to control, so that environmental quality objectives (e.g. in terms of ambient SO_2 concentrations and/or deposition of sulphur to sensitive ecosystems) can be met in the most cost-effective way (Section 4). The method is illustrated by a number of example calculations, demonstrating

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0301-4797/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2004.04.009

a substantial potential for cost saving through emission control strategies that simultaneously target the protection of human health and ecosystems (Section 5). Conclusions are drawn in Section 6.

2. Development of SO_2 emissions in Asia

Over the last decades Asia experienced a rapid increase in energy use and, as a consequence, emissions of air pollutants. It is estimated that SO_2 emissions in Asia grew from 17.1 million tons in 1975 to 38.5 million tons in 1995, i.e. with an average annual growth rate of 4.1% (Streets et al., 2001). Because energy demand is generally projected to further expand in the future with fossil fuels remaining the dominant source (Riahi and Roehrl, 2000), conventional wisdom expects continued growth in sulphur emissions in the coming decades (Nakicenovic et al., 2001). However, recent experience shows that, while such expectations continue to hold true in some countries, they may be outdated in others (Carmichael et al., 2002).

In the early 1990s, with the ambitious plans for economic development in Asia and the lack of stringent emission control regulations, SO_2 emissions were expected to triple until 2020 (Foell et al., 1995). Since that time, however, the growth of SO_2 emissions in Asia has declined. This change is to a large extent due to a reduction of SO_2 emissions in China brought about by several factors: a marked decline in industrial coal use from the closure of small and inefficient plants, a slow-down in the general economic growth, the improved efficiency of energy use, the closure of some high-sulphur coal mines, a general reform of industry and power generation, and a rising awareness of the dangers of air pollution (Sinton and Fridley, 2000). As a consequence, it is estimated that total SO_2 emissions in China have actually declined from 23.8 million tons in 1995 to about 20 million tons in 2000, i.e. a decrease of 3.3% per year. In January 1998, China instituted an SO_2 reduction program—known as the 'two-control-zone' policy—to further abate emissions in industrial and environmentally sensitive regions (Pu et al., 2000). SEPA's National 10th Five-Year Plan for Environmental Protection (SEPA, 2000) aims at an additional 10% reduction until 2005 compared with the 2000 level. Considering these recent trends in the Chinese energy system, a new energy projection was produced by the Chinese Energy Research Institute (presented in Boudri et al., 2002). Based on a projected population growth of 25% between 1995 and 2020 and an increase of GDP by 420%, overall energy consumption would increase until 2020 by no more than 70%. Rapid penetration of natural gas would limit the growth in coal consumption to 25%. This projection implies an annual improvement in energy efficiency of 4.4% per year, which is more than double the historically observed rate.

The RAINS-Asia model (RAINS-Asia, 2001) allows estimating SO_2 emissions based on externally supplied projections of energy use, databases on fuel quality and assumptions on applied emission control measures. In particular, the model makes it possible to quantify for all emission sources the impacts of emission- and fuel standards imposed by legislation.

Table 1
SO_2 emissions and control costs in Asia for the 'Current Legislation' (CLE) and for the hypothetical 'no control' (NOC) and 'best available technology' (BAT) scenarios

	1990	1995	2020		
			CLE	NOC	BAT
SO_2 emissions (million tons)	32.4	36.8	57.0	72.8	11.4
Emission control costs (billion US$ 1995)	2.6	4.7	13.0	0.0	78.3

With the new Chinese energy projection and the present legal regulations on emission controls, the model computes for China a stabilisation of SO_2 emissions after 2010 at about 30 million tons, i.e. 25% higher than 1995[1]. This (bottom-up) estimate suggests higher emissions than the officially published emission target of approximately 18 million tons for 2005 (SEPA, 2000) and the unofficial plans for further reductions thereafter, indicating the need for additional emission controls or for an even more pronounced replacement of coal consumption, if these targets were to be met.

However, other countries, especially in Southeast Asia and on the Indian subcontinent, are expected to further increase their sulphur emissions. With the assumption that the national SO_2 emission standards as decided by 2000 will be fully implemented in all Asian countries (the 'Current Legislation' case), the RAINS-Asia model computes for 2020 an increase of total Asian SO_2 emissions by 75% compared to 1995 (Table 1). Significant variations, though, would occur across countries: increases range from less than 50% (China, Thailand and Singapore) up to factors between two and six (India, Indonesia, Philippines and Pakistan). Emissions in Japan and South Korea are likely to decrease (Table 2).

This continued growth of total Asian SO_2 emissions is substantially lower than anticipated in the early 1990s. As shown in Fig. 1, about two thirds of the 'avoided' SO_2 emissions (between the perspectives of 1994 and 2000) can be attributed to the lower expectations on the growth in energy consumption (due to lower economic growth and higher energy efficiency) and one-third to the emission control measures that were decided after 1995.

By quantifying the determinants of the development of emissions and the technical emission control potential, the RAINS-Asia model allows exploring a hypothetical 'no

[1] For China the estimate includes only current emission and fuel standards, i.e. the maximum concentration limits in flue gases for Phase III (new) plant (Mc Conville, 1997).

Table 2
SO_2 emissions by country, kilotons

	1990	1995	2020		
			CLE	NOC	BAT
Bangladesh	91	106	355	355	107
Bhutan	2	3	16	16	3
Brunei	7	12	19	19	16
Cambodia	25	30	78	78	18
China	20,814	23,823	29,514	35,907	6041
India	3743	4996	12,481	13,149	2037
Indonesia	692	816	1907	2213	414
Japan	1033	850	544	2990	323
Korea (North)	319	225	530	530	125
Korea (South)	1709	1196	1219	3497	501
Laos	5	6	17	17	5
Malaysia	211	253	433	433	76
Mongolia	82	76	133	133	14
Myanmar	25	33	50	50	30
Nepal	19	26	101	101	38
Pakistan	696	987	4235	4235	458
Philippines	453	555	1381	1921	215
Sea Lanes	608	824	1278	1278	219
Singapore	241	285	345	489	55
Sri Lanka	35	47	157	157	35
Taiwan	484	352	493	2047	241
Thailand	1018	1202	1394	2796	269
Vietnam	104	138	394	414	126
Total Asia	32,417	36,841	57,075	72,826	11,368

control' (NOC) situation and the 'best available technology' (BAT) case. These provide, for a given level of energy use, the range within which emissions can be modified by technical emission control measures—from the 'doing nothing' case to full application of all available technical measures. In retrospect, the model analysis reveals that in 1995 3.9 million tons of SO_2 emissions have been captured by control technologies and thus not released to the atmosphere. Valued at international world market prices and ignoring application of potentially cheaper domestic technologies, it is estimated that Asian countries spent in 1995 4.7 billion US$ to control their SO_2 emissions[2].

By 2020, emission control measures will further penetrate as a result of the recent legislative changes. It is estimated that in 2020 28% of the theoretically uncontrolled emissions will be retained by technology at a cost of 13 billion US$ per year (in 1995 prices). It is also clear that present emission standards will not exhaust the full control potential offered by technical means. In the extreme case, present-day technology could reduce Asian SO_2 emissions down to 11 million tons, i.e. by 84%, albeit at costs of 78 billion US$ per year (Table 1).

[2] Information about methodology of calculating emission control costs in RAINS-Asia is included in Annex 1.

3. Ambient SO_2 concentrations and sulphur deposition

Elevated levels of SO_2 in ambient air pose a threat to human health. The World Health Organization (WHO) has recommended an annual average SO_2 concentration of 50 $\mu g/m^3$ not to be exceeded if human health is to be safeguarded (WHO, 2000). The national Chinese standard is set at 60 $\mu g/m^3$.

Many Chinese cities face high SO_2 concentrations. Among the 338 cities surveyed by the Chinese State Environmental Protection Agency (SEPA), nearly 60% of the cities exceeded in 1999 the Class II SO_2 concentration standards (SEPA, 1999). While present ambient SO_2 concentrations in many urban areas on the Indian Subcontinent and in Southeast Asia range below the WHO standard, it is estimated that with current trends sulphur pollution in and around the cities of the Indian Subcontinent might even triple by 2020 (Guttikunda et al., 2003).

Relying on a detailed atmospheric dispersion model (Arndt and Carmichael, 1995; Arndt et al., 1998), the RAINS-Asia model calculates, for any pattern of SO_2 emissions resulting from a user-defined emission scenario, ambient levels of SO_2 and sulphur deposition across Asia. As an example, Fig. 2 displays annual average SO_2 concentrations for the 'current legislation' emissions expected for the year 2020.

These calculations are carried out with a spatial resolution of 1° longitude × 1° latitude (approximately 70–110 km × 110 km). Thus, these model results are representative for ambient concentrations averaged over the area of a grid cell, but do not reflect sub-grid variations. Analyses of monitoring data and results from finer scale dispersion models show that concentrations close to emission sources can exceed in urban areas the grid cell average concentrations by a factor between two and five (Guttikunda et al., 2003).

These calculations indicate that, if energy development continues as presently foreseen in the recent projections, ambient SO_2 concentrations will continue to exceed national and international health standards despite the recently adopted emission control strategies. By 2020, SO_2 concentrations would exceed in some areas 80 $\mu g/m^3$ even on a grid average, particularly in the North-eastern part of China (Shanxi, Shandong, Tianjin, Hebei, Jiangsu), in Shanghai, Guangzhou and Sichuan, and in Pakistan. Violations of the WHO guideline value (corresponding to grid average SO_2 concentrations of 15–20 $\mu g/m^3$) are likely in the urban areas in China, in Bangkok, Korea, India and Pakistan.

Combining the results from the dispersion calculation with the population database of the RAINS-Asia model it is estimated that in 2020 more than 1.1 billion people will live in areas where SO_2 concentrations exceed the WHO guideline. (This result is based on the assumption that SO_2 concentrations within cities are three times above the grid cell average, see also Guttikunda et al., 2003). For comparison, the same calculation yields for 1995 a health

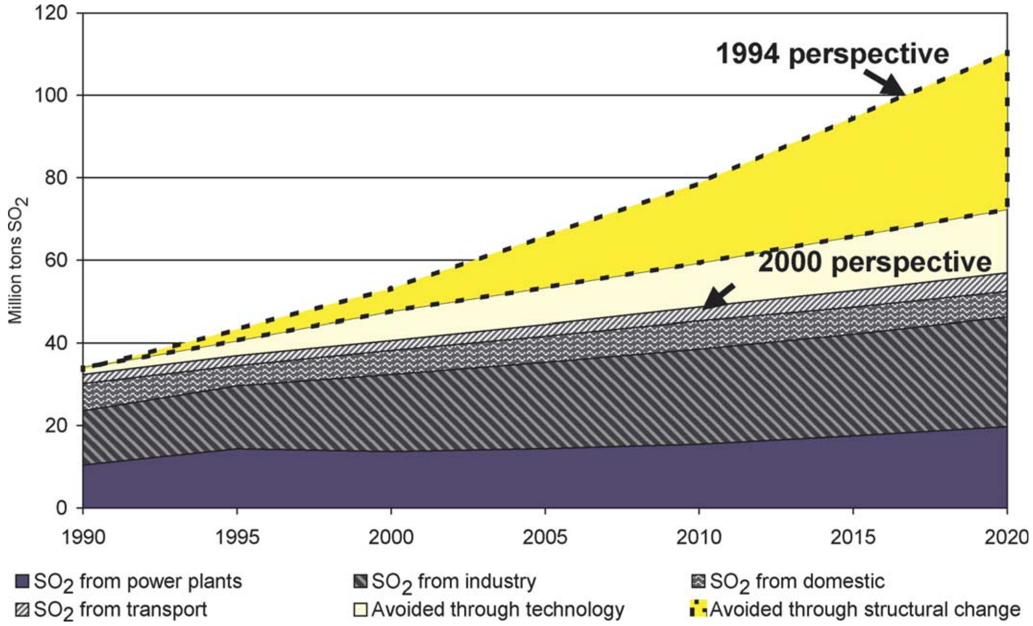

Fig. 1. Trend of SO_2 emissions in Asia. Projections developed in 1994 compared to the expectations in 2000 reflecting the recent changes in energy policy.

threat to about 700 million people. Thus, the number of threatened people is expected to increase by 60% despite the recent improvements in emission control legislation (Table 3). Since health damage from SO_2 emissions can reach significant dimensions also in economic terms (Holland et al., 1998; Markandya, 1996), further control of SO_2 emissions in Asia will be necessary.

Similar conclusions can be drawn for ecosystems damage from sulphur emissions. The RAINS-Asia model allows comparing regional sulphur deposition with sustainable threshold levels at which acidity caused by deposited sulphur can be absorbed by nature and will not cause damage to ecosystems. Such 'critical loads' (Nilsson and Grennfelt, 1988) were determined for a wide range of ecosystems throughout Asia, taking into account Asian-specific conditions (Hettelingh et al., 1995). A comparison of sulphur deposition resulting from the emissions projected for 2020 with such critical loads demonstrates that large shares of the ecosystems in eastern China, Korea, Thailand and Malaysia will remain threatened by harmful sulphur deposition in excess of their sustainable critical loads (Fig. 3). Excess deposition will reach three to four grams sulphur per square meter per year and thus will exceed the critical load by a factor of 3–5.

It can be concluded that, despite the significant financial efforts allocated to the future control of sulphur emissions, in 2020 more than 1.1 billion people (37% of the Asian population) will live in areas where the WHO guideline

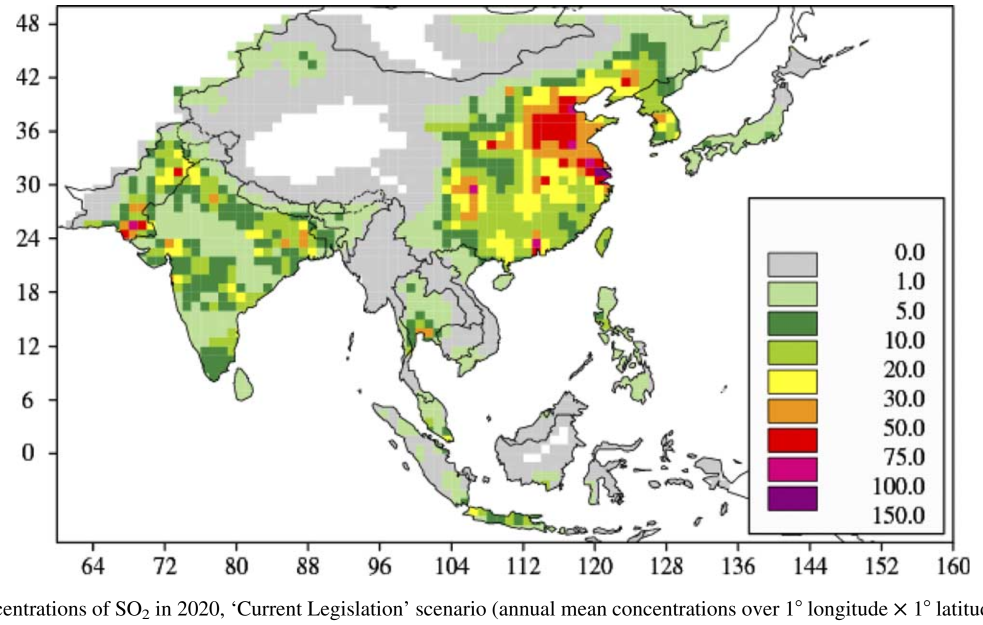

Fig. 2. Ambient concentrations of SO_2 in 2020, 'Current Legislation' scenario (annual mean concentrations over 1° longitude × 1° latitude grid cells, $\mu g/m^3$).

Table 3
Environmental indicators as calculated by RAINS-Asia for the scenarios presented in Table 1

Scenario	Unprotected ecosystems		Population in grid cells with concentrations $>17\ \mu g/m^3$	
	Million hectares	% of total ecosystem area	Million persons	% of Asian population
Current legislation (CLE)				
1990	44	3.6	596	20
1995	49	4.0	693	23
2020	73	5.9	1113	37
No control (NOC) 2020	97	7.9	1318	44
Best available technology (BAT) 2020	4	0.3	0	0

value for SO_2 will be exceeded, and that 73 million hectares of ecosystems will receive harmful sulphur deposition in excess of the sustainable threshold loads. Thus it is likely that further reductions of sulphur emissions will remain on the political agenda in Asia.

4. An optimisation approach to search for cost-effective emission reductions

To safeguard human health and ecosystems, Asia will need to further reduce SO_2 emissions beyond the presently planned level. Since many Asian countries have already introduced legislation to control sulphur emissions, and since the required measures usually target the cheapest options for controlling emissions, additional sulphur reductions will face increasing costs. Thus, the search for cost-effective emission controls will emerge as a critical issue.

The optimisation mode of the RAINS model is a powerful tool that can assist in the search for cost-effective solutions to combat the negative effects of air pollution. In Europe, the optimisation techniques of the European implementation of the RAINS model have been used in several policy contexts to identify cost-effective allocations of emission reductions to meet environmental policy targets. Optimisation results were used to guide international environmental negotiations on the Second Sulphur Protocol of the Convention on Long-range Transboundary Air Pollution (Tuinstra et al., 1999), the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone in 1999 (Amann et al., 1999) and the European Union's Directive on National Emission Ceilings (Amann and Lutz, 2000; Wettestad, 2002).

Section 4.1 provides a brief mathematical description of an optimisation problem for the Asian implementation of the RAINS model, while Section 4.2 presents illustrative results for the Asian situation.

4.1. Formulation of the optimisation problem

The optimisation model distinguishes a set of I area (dispersed) sources and J large point sources of sulphur emissions. The area emission sources i are either countries or sub-national regions (RAINS-Asia distinguishes 22 countries, 103 regions/provinces and 400 large point sources.) There are K receptor areas (grid cells with 1° longitude × 1° latitude resolution), for which ambient SO_2 concentrations and sulphur deposition can be quantified.

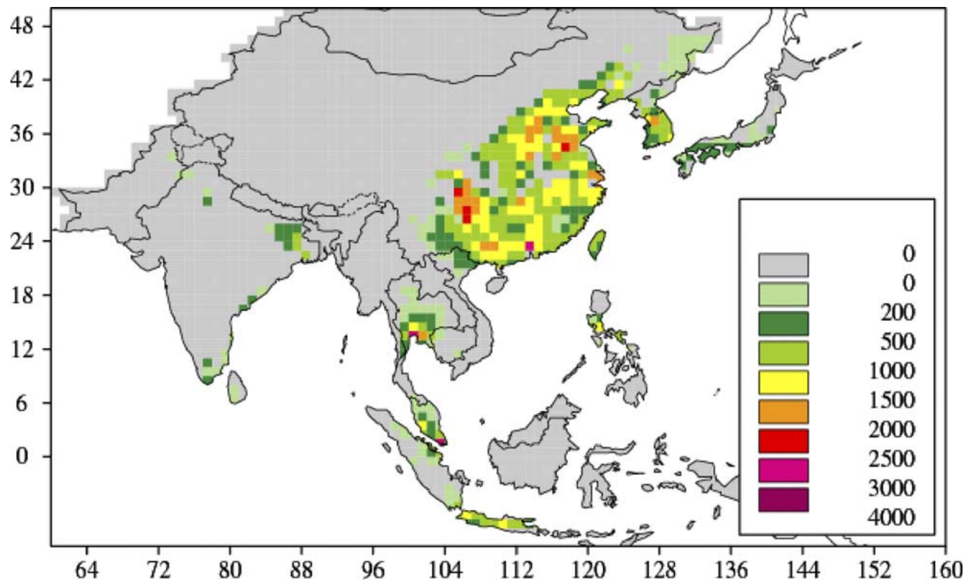

Fig. 3. Excess sulphur deposition in Asia in 2020 above the critical loads, 'Current Legislation' scenario (acid equivalents/ha-yr).

The *decision variables* of the optimisation problem are the annual emissions of sulphur dioxide of area (e_i) and large point (e_j) sources.

Emissions at each source can be modified between bounds, i.e. between the uncontrolled level and the maximum technically feasible reduction.

For area sources

$$e_i^{\min} \le e_i \le e_i^{\max} \tag{1}$$

where

e_i… emission from area source $i (i \in I)$, and for large point sources

$$e_j^{\min} \le e_j \le e_j^{\max} \tag{2}$$

where

e_j… emission from large point source $j (j \in J)$.

These bounds may be optionally tightened, e.g. to reflect upper limits to the emissions related to air pollution control plans developed by local or national authorities. Additional constraints can be imposed on the total emissions of a given region:

$$E_i^{\min} \le e_i + \sum_{j \in J_i} e_j \le E_i^{\max} \tag{3}$$

where

$E_i^{\min}, E_i^{\max}$… minimum and maximum emissions in region i,
J_i… set of large point sources located in region i.

For each source, emission control costs are described as piece-wise linear functions of the emission (reduction) level (e_i, e_j). RAINS-Asia estimates control costs based on technology- and country-specific cost parameters of individual technologies (Cofala et al., 2000). The model calculates the marginal costs of each control option and constructs cost functions by ranking all available abatement options according to their marginal costs. This methodology produces piece-wise linear curves, consisting typically of several dozens of segments for each source.

Depending on the purpose of the analysis, the user can either employ cost curves starting from the uncontrolled situation or focus on emission control options that remain after implementation of certain emission and fuel standards, e.g. those imposed by current legislation. The cost curve algorithm is explained in detail in Cofala and Syri (1998).

A stylised example of a cost curve is presented in Fig. 4. The marginal costs for each individual measure are plotted on the y-axis against the remaining emissions after implementation of a given set of control measures on the x-axis. The illustrative cost curves presented in this graph take as a starting point the emission reductions and costs of already installed control equipment and ignore potentially cheaper options for these sources. Premature scrapping of already installed equipment is excluded. For new capacities, which are not yet commissioned, the algorithm picks the most cost-effective realisation that achieves the legally required emission cuts. Special constraints prohibit unrealistic implementation rates.

For each receptor point, sulphur deposition (ds_k) is related to the decision variables e_i and e_j via a set of deposition constraints $ds_k^{\max}$:

$$ds_k = tss * \left(\sum_i ts_{ik} e_i + \sum_i ts_{jk} e_j \right) + ks_k \le ds_k^{\max} \tag{4}$$

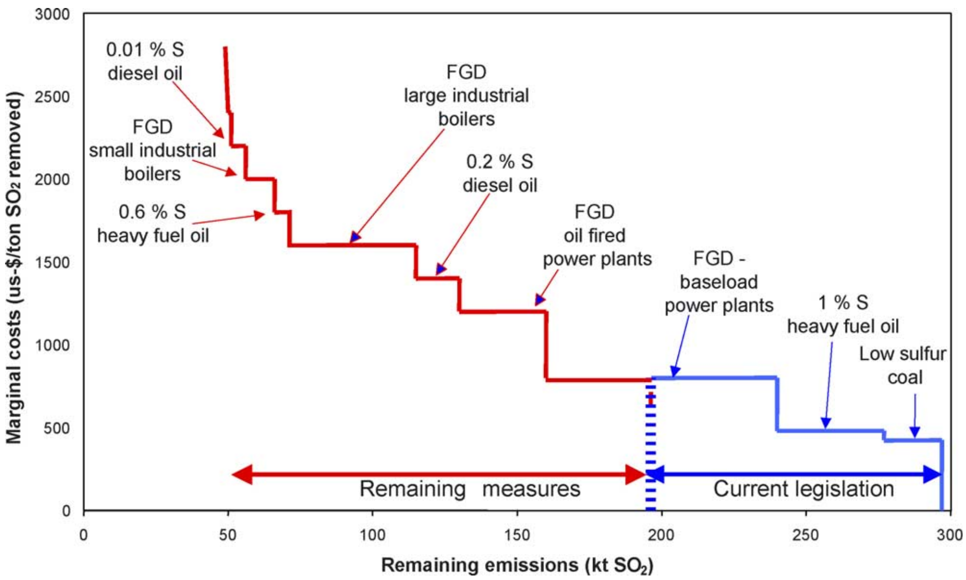

Fig. 4. An example SO_2 emission reduction cost curve, ranking the available emission control measures (use of low sulphur coal, FGD: flue gas desulphurization, etc.) according to their cost-effectiveness.

where

ts_{ik}, ts_{jk}… sulphur deposition transfer coefficients for area- and large point sources,
ks_k… background sulphur deposition in grid cell k,
tss… scaling factor to convert sulphur deposition into units of acidity used in the quantification of critical loads.

A similar set of constraints $ac_k^{\max}$ is specified for ambient concentrations ac_k :

$$ac_k = \left(\sum_i tac_{ik} e_i + \sum_i tac_{jk} e_j \right) + kac_k \le ac_k^{\max} \quad (5)$$

where

tac_{ik}, tac_{jk} SO_2 concentration transfer coefficients for area- and large point sources,
kac_k background ambient concentration in grid cell k.

The sulphur deposition transfer coefficients ts_{ik} specify the proportion of total emissions from a source i that is deposited at a receptor point k. Similarly, the transfer coefficients for ambient concentrations ac_{ik} determine to what extent emissions from a source i contribute to ambient concentrations of SO_2 at a receptor point k. Background depositions and concentrations (ks_k and kac_k, respectively) specify the contributions from natural sources (e.g. volcanoes) and sources outside the model domain. The RAINS model extracts this information from more detailed atmospheric dispersion models.

A user may specify deposition targets $ds_k^{\max}$ in relation to the sensitivity of ecosystems in each grid cell (the so-called critical loads for sulphur) or may base the quantification of his 'policy' targets on other concepts. International or national air quality standards can be used to define constraints on ambient concentrations of SO_2.

In the optimisation problem, the *objective function* is to minimise total costs of sulphur emission reductions subject to the constraints specified for deposition and/or concentration:

$$\text{objective\_function} = \sum_i c_i(e_i) + \sum_j c_j(e_j) \Rightarrow \min \quad (6)$$

Table 4
Emissions, costs and environmental effects for the optimised scenarios

Scenario name (and abbreviation)	SO_2 emissions (Million tons)	Emission control costs (Billion $US\$_{95}$/ year)	Unprotected ecosystems		Population exposed to grid average SO_2 concentrations > 17 μg/m^3	
			Million hectares	Total ecosystems area (%)	Million people	Total population (%)
Current legislation (CLE)	57.0	13.0	73	5.9	1113	36.8
Optimised scenarios:						
SO_2 concentrations lower than:						
50 μg/m^3 (C50)	54.9	14.2	71	5.8	1098	36.3
25 μg/m^3 (C25)	45.9	19.5	61	5.0	970	32.1
17 μg/m^3 (C17)	38.4	26.1	42	3.4	0	0.0
Emissions in each region lower than in:						
2000 (EM00)	39.7	25.1	55	4.5	750	24.8
1995 (EM95)	35.9	28.7	43	3.5	656	21.7
1990 (EM90)	29.5	34.6	34	2.8	564	18.6
Sulphur deposition in each grid cell lower than in:						
2000 (D00)	40.3	24.6	51	4.1	729	24.1
1995 (D95)	36.3	28.2	41	3.3	636	21.0
1990 (D90)	31.6	32	34	2.7	550	18.2
Excess S deposition in each grid cell lower than in:						
2000 (EX00)	47.4	19.7	49	4.0	847	28.0
1995 (EX95)	44.7	21.5	41	3.4	754	24.9
1990 (EX90)	41	23.6	35	2.8	685	22.6
Excess S deposition lower than in 2000 and SO_2 concentrations below:						
25 μg/m^3 (C25EX00)	40.5	23.4	43	3.5	797	26.3
17 μg/m^3 (C17EX00)	34.8	28.9	32	2.6	0	0.0

4.2. Examples of cost-efficient scenarios

The optimisation problem was implemented in RAINS-Asia, distinguishing emission controls in 103 source regions and 400 large point sources. To illustrate the capabilities of the model and to demonstrate how optimised results depend on the type of the target, five types of optimisation runs are presented in this paper. All calculations start from the volume and structure of energy consumption projected for the year 2020 and search for the cost-minimal allocations of emission reductions that achieve the following environmental targets:

- *SO_2 concentration limits*: the annual average *ambient SO_2 concentrations* in each grid cell are constrained below (i) 50 μg/m^3, (ii) 25 μg/m^3, and (iii) 17 μg/m^3 (Scenarios C50, C25 and C17);
- *Emission limits*: bring *total emissions* in each region back to the levels of the year (i) 2000, (ii) 1995, and (iii) 1990 (Scenarios EM00, EM95 and EM90);
- *Deposition limits*: Bring *sulphur deposition* in each grid cell back to the levels of (i) 2000, (ii) 1995, and (iii) 1990 (Scenarios D00, D95 and D90);
- *Excess deposition limits*: bring harmful *excess sulphur deposition* (i.e. sulphur deposition exceeding the critical loads) in each grid cell back to the levels calculated for (i) 2000, (ii) 1995, and (iii) 1990 (Scenarios EX00, EX95 and EX90);
- *Combined limits on concentration and excess deposition*: keep average *ambient SO_2 concentrations* in each grid cell below (i) 25 μg/m^3, (ii) 17 μg/m^3 and, at the same time, bring *excess sulphur deposition* back to the level of the year 2000 (Scenarios C25EX00, C17EX00).

For the examples presented in this paper, the optimisation explores the cost-effective emission controls on top of current legislation (formulated as bounds for the decision variables, $E_i^{\max}$), so that the present legislation will not be reversed.

The results clearly demonstrate that the cost-optimal allocation of emission controls resulting from the optimisation is crucially determined by the type of environmental targets (constraints) specified by the user. For instance, costs for the emission limit scenarios range between 25.1 and 34.6 billion US$ per year, depending on the level of ambition, with higher costs for targets that require more emission reductions (see Table 4 for aggregated results). The scenarios also demonstrate that the cost-effectiveness of emission control strategies can be increased if targets are specified in relation to environmental sensitivities. This is illustrated in Fig. 5 (left panel), showing that the 'EM' scenarios that bring back emissions to historically observed levels are more expensive—at comparable levels of ecosystems protection—than scenarios that target at deposition or, in the most efficient case, at harmful excess deposition. For the environmental objective of

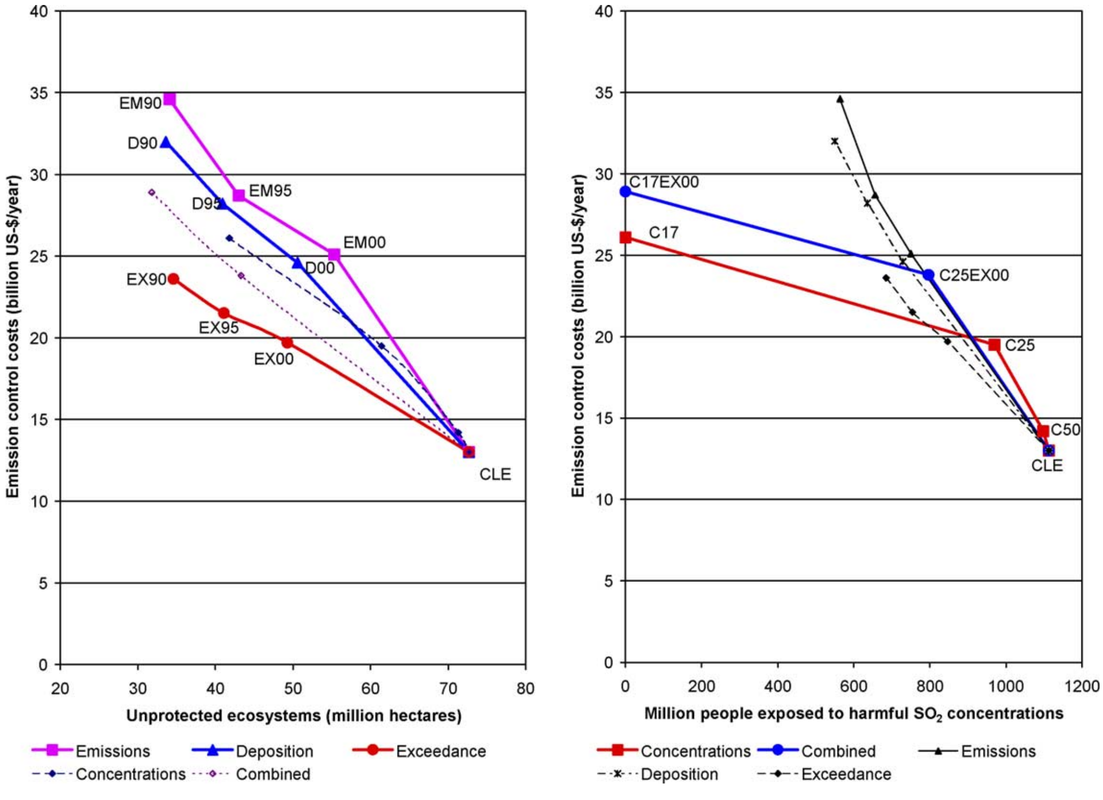

Fig. 5. Cost-effectiveness of the different types of optimized scenarios. Emissions (EM): emission-related optimization targets, deposition (D): deposition-related targets, Exceedance (EX): critical loads exceedance-related targets.

re-establishing the environmental situation of 1990, returning harmful excess deposition back to the 1990 values would be more than 10 billion US$ per year cheaper than simply bringing emissions in the various countries and regions down to their 1990 levels. Obviously, the optimisation allocates in the first case emission controls to those sources that contribute most to harmful excess deposition at the sensitive ecosystems, but does not request emission controls for sources in ecologically less sensitive areas that do not cause environmental damage.

For the current legislation (CLE) case, for which control costs are estimated at 13 billion US$ per year, the model calculates more than 1.1 billion people living in areas where the WHO guideline value will be exceeded. Bringing down grid-average concentrations everywhere below 25 $\mu g/m^3$ (Scenario C25) would leave 970 million people unprotected at costs of 19.5 billion US$ per year. Emission controls could be gradually tightened up to a level where all Asian people would be protected at a cost of 26.1 billion $ (Scenario C17). However, in this case 42 million hectares of ecosystems would still receive unsustainable sulphur deposition.

It is important to note that population exposure to dangerous SO_2 concentrations does not always spatially coincide with excess sulphur deposition that causes damage to ecosystems. Population is placed at different locations than sensitive ecosystems, and concentration patterns resulting from a given emission field are different from the spatial distribution of sulphur deposition. Thus, an optimisation targeting health protection will put different priorities on emission controls than a strategy that has the objective to protect natural ecosystems. This is illustrated in Fig. 5, showing that the scenarios for population and ecosystems protection have different effectiveness for the different purposes.

The optimisation mode of the RAINS-Asia model allows exploring emission control strategies that simultaneously address both negative consequences of sulphur emissions. Indeed, the scenarios with combined targets appear as attractive. For instance, Scenario C17EX00 reduces not only ambient concentrations below the WHO guideline value, but decreases at the same time also the area of unprotected ecosystems by 60% compared to the current legislation case. Although the costs for this scenario are approximately the same as the cost of reducing the emissions in Asia down to the level of 1995 (Scenario EM95), the environmental effects are much larger. Additional 11 million hectares of ecosystems are protected, and additional 22% of Asia's population will live in areas with SO_2 concentrations below the WHO threshold. It should be mentioned that this scenario does by no means exhaust the technical potential for controlling SO_2 emissions in Asia; its costs amount to only 37% of the cost of fully implementing best available control technologies.

Obviously, the emission controls suggested in an optimised scenario depend on the environmental situation in a country as well as on the stringency of the target. To illustrate this aspect, Table 5 presents country-specific emission reductions for the following three scenarios:

- Reduction of excess deposition below the level experienced in 2000 (EX00);
- Reduction of grid-average ambient concentrations below 25 and 17 $\mu g/m^3$, respectively (C25 and C17);
- Combined targets for excess deposition and ambient SO_2 concentrations (C25EX00 and C17EX00).

Table 5
Emissions reductions optimised for alternative environmental targets (percentage changes compared to the 'Current Legislation' (CLE) case)

Country	Constraints on				
	Excess deposition	Concentration		Concentration and excess deposition	
	EX00	C25	C17	C25EX00	C17EX00
China	-14	-30	-48	-34	-48
India	-17	-4	-11	-18	-21
Indonesia	-37	0	-1	-37	-37
Korea (North)	-43	0	-30	-17	-30
Korea (South)	-38	-37	-46	-40	-46
Malaysia	-34	0	0	-34	-34
Pakistan	-2	-32	-47	-32	-47
Philippines	-51	0	-3	-51	-51
Singapore	-33	0	-27	-33	-33
Sri Lanka	-22	0	0	-22	-22
Taiwan	-28	0	0	-26	-22
Thailand	-46	-13	-22	-46	-46
Vietnam	-18	0	0	-18	-20
Total Asia	-17	-20	-33	-29	-39

Only countries where measures are necessary are listed in the table.

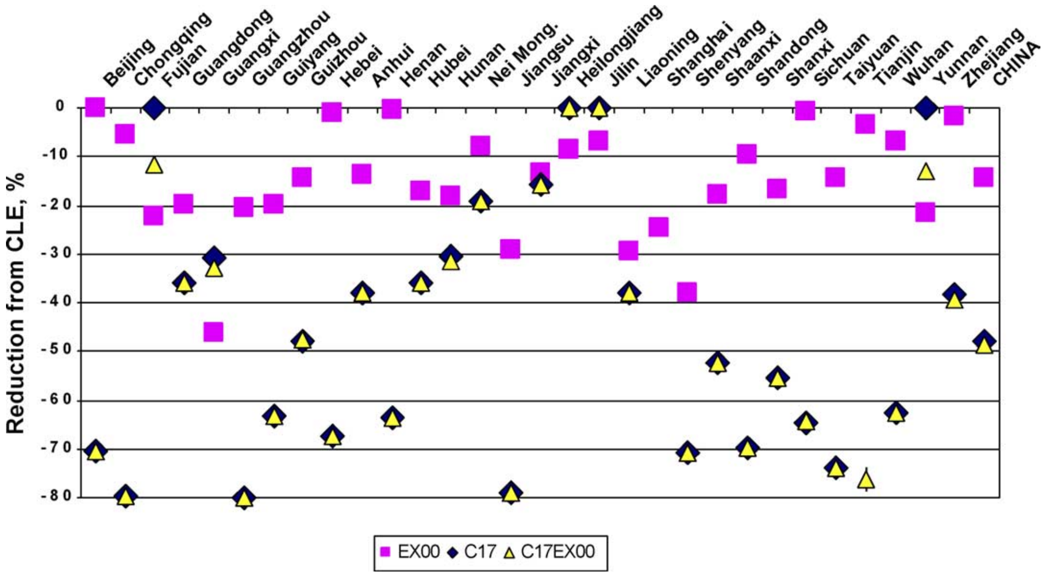

Fig. 6. Sulphur emission reductions by RAINS-Asia regions in China for scenarios with three different environmental targets.

For all these targets, nine countries (Bangladesh, Bhutan, Brunei, Cambodia, Japan, Laos, Mongolia, Myanmar, Nepal) would not need to reduce their SO_2 emissions below what is presently planned for 2020 (i.e. the CLE case). In seven other countries (Indonesia, Malaysia, Philippines, Singapore, Sri Lanka, Taiwan, and Vietnam), the extent of required emission controls is determined by the stringency of the deposition-related targets, while the concentration targets would be achieved as a side effect. In the remaining countries, including China and India, both deposition and concentration targets are driving the emission reductions.

Since the dispersion of SO_2 in the atmosphere is not uniform, the reduction requirements are region-specific, which is illustrated in Fig. 6 for China. The graph presents emission reductions by province for three scenarios (EM00, C17 and C17EX00) relative to the reductions expected from current legislation. For some provinces (e.g. Beijing, Hebei, Henan, Sichuan, Zhejiang), the regional emission ceilings are solely determined by the concentration constraints. In turn, in Fujian, Guangxi, Heilongjiang, Jilin, and Yunnan, emissions reductions are driven by deposition constraints. For other provinces, the ceilings required for the health-related scenarios are stricter than those of the ecosystems oriented scenarios.

It must be emphasized that the selection of the type and the stringency of the environmental target is a political, not a scientific choice. Nevertheless, the analysis of costs and benefits for different targets, which is possible with the use of the optimisation routine presented in this paper, provides decision makers with relevant information about available choices and their consequences.

5. Summary and conclusions

Current sulphur pollution levels in Southeast Asia are harmful to natural ecosystems and to human health. Although the slower economic growth of the recent years, the switch to cleaner fuels and the recently adopted emission control legislation in many Asian countries should lead to lower growth of sulphur emissions in Asia than it was anticipated earlier, the improved legislation does not appear as sufficient to achieve safe levels of air quality in Asia. With continued economic growth, emissions are likely to grow further and additional control of SO_2 emissions will most likely remain an issue in Asia.

Since additional control measures that are not required by current regulations are becoming increasingly costly, future strategies should carefully target emission controls to those sources that contribute to environmental damage and are cheapest to control. Based on scientific information about the atmospheric dispersion and the environmental effects of pollution, integrated assessment models, such as RAINS-Asia, have been developed to provide tools for systematically exploring cost-effective emission control strategies.

The example scenarios presented in this paper clearly indicate a significant scope for cost savings of optimised emission control strategies that are driven targeted at the harmful effects of pollution, compared with traditional approaches that determine emission controls solely in relation to historical emission levels. Obviously, in such optimised strategies the distribution of emission controls across the various sources is critically determined by the type and stringency of the environmental target. Protecting population from exposure to dangerous SO_2 levels will result in different allocations of measures than strategies that aim at the protection of ecosystems. It has been shown in this paper that, with the help of integrated assessment models, combined strategies can be developed that simultaneously address both issues. Such combined strategies can point the way toward making best use of resources for protecting human health and vegetation.

The present implementation of RAINS-Asia addresses continental scale long-range sulphur pollution, with a limited spatial resolution for individual hot spot areas. In principle, the RAINS-Asia framework could also be applied with finer spatial resolution to look at air pollution problems within heavy polluted regions, provided that appropriate data on emissions and atmospheric dispersion are available with the required spatial resolution.

Ultimately, any analysis of air pollution control strategies in Asia should include other pollutants and environmental effects beyond sulphur so that through a ‘multi-pollutant/multi-effect’ approach the cost-effectiveness of emission controls could be further enhanced. For this purpose, the RAINS-Asia optimisation framework should be extended to other pollutants (fine particles, nitrogen oxides, non-methane volatile organic compounds, ammonia, greenhouse gases) and other environmental effects (health impacts of fine particles and ground-level ozone, eutrophication, radiative forcing, etc.).

Acknowledgements

Part of the work presented in this study was funded by the European Commission, DG Research (contract number ERBIC18CT960098). See also www.dow.wau.nl/msa/renewables and www.iiasa.ac.at/rains.

Appendix A. Costs of emission control technologies in RAINS-Asia

SO_2 emissions from energy combustion can be reduced through energy conservation, fuel substitution, fuel desulphurization, the use of low sulphur fuels, combustion modification (i.e. addition of sorbent to the furnace), conventional flue gas desulphurization and advanced methods of sulphur capture from flue gases. The assessment of costs and benefits (in terms of emissions reduction) of energy conservation and fuel switching requires detailed modelling of the technical options available for the energy system of a given country, which is beyond the continental scope of the RAINS model.

Thus, the RAINS model concentrates on the following five categories of measures:

- The use of low sulphur fuels;
- In-furnace control of SO_2 emissions (e.g. through limestone injection);
- Conventional wet flue gas desulphurization;
- Advanced methods of sulphur capture from flue gases;
- Various methods for controlling industrial process emissions.

To assess the energy conservation and fuel substitution, detailed national energy models are necessary to capture the complex interactions of modifications within the energy systems. Such national models can be used to generate new energy scenarios, which can then be implemented in the RAINS model to assess their environmental impacts.

The cost of using low sulphur fuels is reflected in the RAINS model through a price premium for low sulphur fuels, derived from the avoided fuel desulphurization costs (Table A1).

For add-on technologies, the cost evaluation is based on international operating experience of pollution control equipment by extrapolating it to the country-specific situation of application. A free and competitive market for the exchange of emission control technology is assumed. Important country-specific factors with strong impacts on abatement costs are the characteristic sulphur content of fuels, plant capacity utilization regimes, boiler sizes, prices of local inputs (labour, electricity, sorbents, waste disposal, etc.). Details on the costs calculation method and data sources are provided in Cofala et al. (2000). Asia-specific data have been verified and updated by Akimoto et al. (2000) and are contained in RAINS-Asia (2001).

Table A2 illustrates the influence of the various parameters (abatement technology, fuel type and fuel quality as well as boiler type and operating conditions) on the abatement costs calculated by RAINS-Asia. Costs per ton of SO_2 abated differ between sources by an order of magnitude, opening a scope for cost savings through optimisation.

Table A1
Cost of low sulphur fuels in RAINS-Asia

Technology	Sulphur content (%)		Price premium (US$/(PJ*% S))	Cost (US $/t SO2)
	Initial	Low sulphur		
Low sulphur hard coal (25 GJ/t)	1.0	0.6	0.41	539
Low sulphur heavy fuel oil (42 GJ/t)	3.0	0.6	0.34	714
Low sulphur diesel (44 GJ/t):				
Stage 1	0.6	0.2	1.01	2224
Stage 2	0.2	0.05	3.03	5454
Stage 3	0.05	0.005	9.98	19,926

Table A2
Examples of costs of add-on control technologies for combustion sources in RAINS-Asia

Technology/sector	Fuel	Fuel quality	Removal efficiency (%)	Capital investments (US $/kWth)	Fixed O + M (%)	Variable O + M (US$/GJ fuel)	Unit cost	
							US$/GJ fuel	US$/t SO2
We flue gas desulphurisation								
Power plants—new (1000 MWth, 7000 h/a)	Brown coal	8 GJ/t, 1.5% S	95	81	4	140	456	183
Power plants—new (1000 MWth, 6000 h/a)	Hard coal	25 GJ/t, 1.0%S	95	68	4	80	387	536
Power plants—retrofit (360 MWth, 4000 h/a)	Hard coal	25 GJ/t, 1.0%S	90	122	4	81	1047	1531
Industrial boilers (150 MWth, 2500 h/a)	Hard coal	25 GJ/t, 1.0%S	85	103	4	84	1389	2150
Industrial boilers (150 MWth, 2500 h/a)	Heavy fuel oil	42 GJ/t, 3.0% S	85	93	4	104	1278	1053
In-furnace control (limestone injection)								
Power plants—new (360 MWth, 4000 h/a)	Hard coal	25 GJ/t, 1.0%S	60	51	4	204	608	1332
Industrial boilers (150 MWth, 2500 h/a)	Hard coal	25 GJ/t, 1.0%S	60	44	4	208	766	1681

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