Some Perspectives of the Major Biogeochemical Cycles
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CHAPTER 9

Socio-Economic Impacts of the Effects of Man on Biogeochemical Cycles: Sulphur

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ABSTRACT

Acidification of poorly buffered freshwaters accompanied by losses in fish population has occurred in large regions of northern Europe and eastern North America. These regions receive acid precipitation (pH 4.5) and are underlain by granitic or similar bedrock with thin and patchy soils.

Socio-economic effects of damage to the freshwater aquatic system are losses in commercial fishing and income from tourism including sport fishing. Such effects may be expressed in monetary terms. This is not the case for the destruction of freshwater ecosystems as such. An alternative evaluation would be to calculate the cost for restoring damaged ecosystems. The costs of liming are estimated.

There are a number of technical solutions available to reduce sulphur dioxide emissions. The obstacles are mainly of an economic nature. The typical costs of fuel oil and flue gas desulphurization are given.

Great variations exist in emission density and in emission per capita of sulphur dioxide within the European region. A reduction in sulphur dioxide emissions in Europe from the present level of 60 million tons to 25 million tons per year would cost about \$10 billion (\$$10^{10}$) annually.

9.1 INTRODUCTION

Atmospheric studies in recent years have substantially extended our knowledge of the origin and behaviour of sulphur oxides in the atmosphere. It has been shown that sulphur oxides travel over long distances and emissions in one country can contribute significantly to sulphate aerosol concentration and acid deposition in another country (OECD, 1977).

Sulphate aerosols have an indisputably adverse effect on visibility. Among obvious types of damage associated with visibility impairment are aesthetic and psychological costs, loss of property values, loss of tourist revenues in scenic areas, reduction in sunlight, hindrance to aviation, and general citizen dissatisfaction. Sulphate

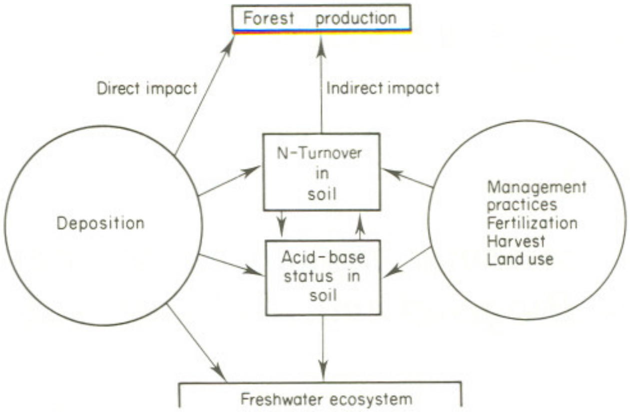

Figure 9.1 Acid deposition affects freshwater and forest ecosystems directly and indirectly (by changing the nitrogen turn-over and acid-base status in soil). The indirect impact is difficult to separate from the impact of local changes in land use and management

aerosols may also pay a significant role in climate modification as important constituents in atmospheric fine particulates affecting the transfer of radiative energy in the atmosphere.

Suspected health effects of sulphate aerosols are not fully supported by existing data.

Wet and dry deposition of acids, due primarily to anthropogenic sulphur dioxide emissions, is now recognized as a threat to terrestrial and aquatic ecosystems on both sides of the North Atlantic.

This paper deals with the socio-economic impacts of the ecological effects of acid deposition, and the methods and costs for sulphur dioxide abatement.

9.2 ECOLOGICAL EFFECTS OF ACID DEPOSITION

There is no simple relationship between acid deposition and effects on freshwater and terrestrial ecosystems (Figure 9.1). The effect of acid deposition on lakes and streams depends on the ability of the catchment area to neutralize acidity. There is little argument that the pH of poorly buffered lakes in southern Scandinavia and eastern North America has decreased by 1-2 units during the last 30 years: from levels generally above pH 6 to values below pH 5. In consequence, aquatic life at all levels has suffered. These regions receive acid precipitation ($\mathrm{pH} < 4.5$) and are underlain by granitic or similar bedrock with thin and patchy soils.

Changes in land use and management practices, e.g. replacing birch by spruce in forestry, may affect the acid-base status in soil and consequently the lakes and streams in the area. It is very unlikely, however, that these factors could explain the

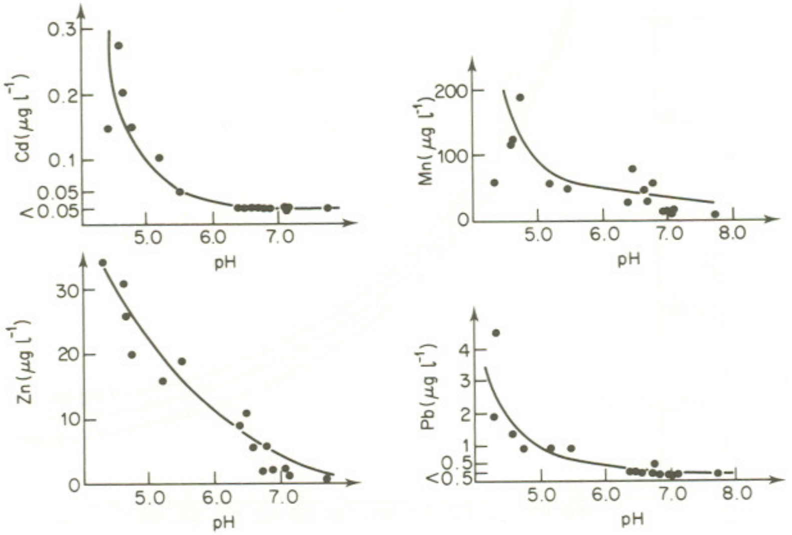

Figure 9.2 Concentrations of metals in 16 lakes with different pH-values on the Swedish west coast. The atmospheric deposition of metals is similar for all lakes. Survey from December 1978 by the Water Research Laboratory, Swedish Environment Protection Board

acidification of freshwater ecosystems in large regions in Norway (Braekke, 1976), Sweden (Ministry of Agriculture, 1978) Canada (Beamish, 1976), and the USA (Likens, 1976). On the contrary the Norwegian SNSF project gives strong evidence for acid deposition as the major source of regional freshwater acidification.

In the SNSF project extensive surveys of the fish populations and chemistry in Norwegian lakes south of 63°N have revealed that the majority of the most acidic lakes have lost their trout populations in recent years. Small lakes at higher altitudes are generally first affected. Similar reports of fish extinction in acidified regions are known from Sweden, Canada, and the USA. No other environmental factor than water acidity seems to explain the gradual regional loss of these fish populations. Indications are that egg and fry mortality are the main cause for failing reproduction, but during large decreases in pH, particularly in spring snowmelt and during heavy autumn rain, acute fish kills have been observed. The tolerance to acid stress in fish depends on many factors, such as content of salts in the water, fish age, size, and genetic background.

Acid lakes are often characterized by higher concentrations of aluminium, manganese, zinc, and cadmium as compared to concentrations of these elements in otherwise similar but less acid lakes. Results from Swedish measurements given in Figure 9.2 can be explained by increased leaching of these metals from the soil. Indications of a significant deterioration in soil chemistry are supported by findings of acid ground water with high metal concentrations in some areas affected by

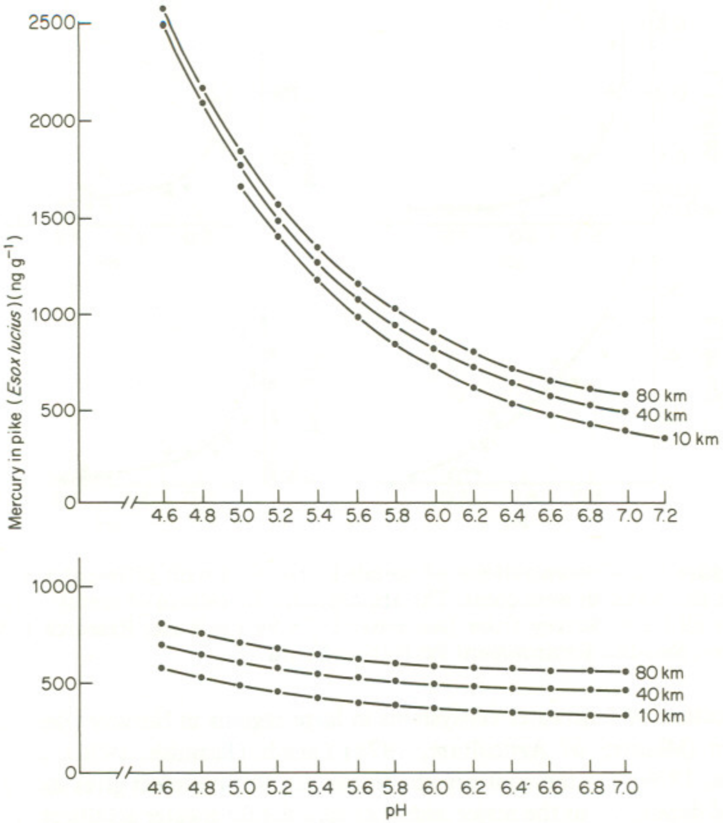

Figure 9.3 Concentrations of mercury in pike (*Esox lucius*) (muscle wet weight) in lakes with different pH-values. The upper curves represent 25 lakes at various distances from a chlor-alkali plant. The curves below represent 31 lakes in a reference area at various distances from the Swedish west coast (Björklund and Norling, 1979)

acid deposition. Aluminium is known to be toxic to fish in the pH range 4.5-5.5 (Schofield, 1977). Mobilization of metals like cadmium and lead as a consequence of acidification must be taken very seriously (Almer *et al.*, 1978).

High concentrations of mercury in fish are correlated with low pH values in water as shown in Figure 9.3. There may be several reasons for this. One important factor is that pH affects the concentrations of individual mercury complexes in water. Such a change in the natural chemical equilibrium may have an impact both on the transfer of mercury between water and air and on the uptake of mercury in fish. The main objectives of the Swedish Environment Protection Board's research programme on mercury are to clarify the effects of acidity on the biogeochemical cycle of mercury and to explain the high concentrations of mercury in fish.

9.3 APPROACHES TO ESTIMATE THE SOCIO-ECONOMIC IMPACTS OF ACID DEPOSITION

The economic and recreational impacts related to the widespread loss of fish stocks may be expressed in monetary terms. In Sweden the area affected by acidification has been estimated to be about 100 000 km^2 comprising 20 000 lakes with a total area of 500 000 ha. The cost due to a total loss of productivity of fish-stocks caught in freshwater and a decreased productivity of fish-stocks caught in the open sea, but breeding in freshwater, has been estimated to be $20–30 million per year (OECD, 1980).

Sport fishing is one of the most popular out door activities in many countries. The acidified lakes and streams in Sweden are of special interest for sport fishing as they are situated in the most populated areas. A total loss of sport fishing has been valued at $50–100 million based on a number of 500 000 sport fishermen in the affected area willing to pay $100–200 per year. The willingness of each fisherman to spend this amount of money was determined in an independent study.

The economic damage caused is important regionally and locally rather than nationally. The money spent on tourism and fishing is of particular importance in certain areas where the local population relies on a combination of farming, forestry, part-time fishing, and tourism for its income. The disappearance of the income from fishing and tourism may jeopardize the livelihood of the local people.

An attempt to evaluate the cost of the destruction of these freshwater ecosystems can be made by calculating the costs for restoring the damaged ecosystems. Liming of affected areas has been proposed as a way to counteract acidification. Based on a test programme launched in 1977, the costs of liming acidified lakes in Sweden have been estimated at $45–75 per ton of limestone (Dickson, 1979). The annual amounts needed to compensate for the acid deposition would be about one million tons of limestone at a total cost of $45–75 million. To compensate for the total acid deposition from the last 30–40 years would cost $1500–3500 million.

Until now anthropogenic acid deposition from sulphur emissions has not been shown to affect adversely the growth of plants except in the vicinity of emission sources. There is, however, a growing concern among scientists for the longer term effects especially on forest productivity. The difficulties in evaluating the effects of acid deposition on forest productivity are related to the fact that it takes 70–100 years for a forest to reach its commercial value. In addition nitrogen oxides contribute to acidification but have at the same time a fertilizing effect. The effect on forestry of deposition of acids has to be kept under review as even a small negative change in productivity has considerable economic consequences.

The economic impacts of the effects of man on the biogeochemical sulphur cycle can also be estimated from a very different starting point.

If we accept that the proved and potential ecological effects of acid deposition are so serious that they cannot be tolerated in the long term we can calculate the costs of controlling anthropogenic sulphur emissions to a 'tolerable' level. Such an approach is justified as the present emissions are in conflict with the declaration of the UN Conference on the Human Environment in Stockholm 1972 which says:

> States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.

What is a 'tolerable' level of sulphur emission in Europe? If we look at the growth rate of the emissions we find that they were fairly constant, around 25 million tons sulphur dioxide per year, during the period 1919–1950. The acidification of aquatic and terrestrial ecosystems seems to be linked to the growing emissions after the second world war. Therefore, the upper limit of 'tolerable' sulphur dioxide emissions in Europe as a whole may be set at 25 million tons. The actual figure is probably lower and will depend on the emissions of nitrogen oxides as they contribute to acidification. It is not necessary, however, to determine the figure with any accuracy for the moment because the control of sulphur emissions has to be a stepwise procedure. The first step must be to stop the increase of the emissions.

There are a number of technical solutions available to reduce sulphur dioxide emissions. The obstacles are mainly of an economic nature.

9.4 METHODS AND COSTS OF SULPHUR DIOXIDE ABATEMENT

The available methods for the control of sulphur dioxide emissions can be classified under give general headings.

(i) Fuel desulphurization processes, in which sulphur is removed from the fuel while the essential nature of the fuel remains unchanged.
(ii) Fuel conversion processes, where the physical state of the fuel is changed, thereby making possible the removal of sulphur.
(iii) Combustion techniques, where an additive is injected which combines with the sulphur.
(iv) Flue gas desulphurization, where sulphur is absorbed from the flue gas produced by combustion.
(v) Fuel substitution, where a high sulphur fuel is replaced by one of lower sulphur content; the replacement of fossil-fired power stations by nuclear energy also falls in this category.

9.4.1 Fuel Desulphurization

For obvious reasons, coal washing is best located close to the source of coal, so that reject material produced in the washing process may be disposed of in the coal mine. In addition centralized coal washeries facilitate the control of any pollution or environmental impact which might arise from this form of fuel desulphurization.

Table 9.1 Typical Cost of Fuel Oil Desulphurization

Desulphurization capacity:	barrels per day	25 000	50 000	100 000
	tons per year $\times 10^6$	1.25	2.4	5.0
Installed cost ($\$ \times 10^6$)		52	80	132
Production Costs ($\$$ year $\times 10^6$)				
Feedstock loss (inc. hydrogen)		4.6	9.1	18.2
Utilities		2.7	5.5	11.0
Catalyst		1.1	2.1	4.2
Maintenance		1.4	2.2	3.6
Labour		15.6	24	39.6
Total		25.4	42.9	76.6
Premium $\$$/ton fuel oil		21.4	18.4	15.6
Additional power cost mils/kW h		5.3	4.5	3.8

Basis: (1) sulphur content of fuel 3.0% sulphur, desulphurization to 1.0% sulphur; (2) hydrogen unit and sulphur recovery system included in capital costs; (3) offsites taken as 20% of process units; (4) capital charge of 30%; (5) all costs in 1978 dollars, instantaneous erection; (6) 8300 operating hours per year.

Furthermore, coal washing is only worthwile if a significant portion of the sulphur in the coal is in the form of pyrites, which is amenable to removal by washing.

Gas cleaning must be accompanied by a means of sulphur recovery. Such installations, for reasons of economy and practicality, should therefore be located at the gas production facilities. In this way, only gas low in sulphur is produced, and this is suitable for either large or small scale combustion applications.

Oil desulphurization is essentially a chemical process, and this is not well known to utility companies. In addition to the desulphurization operation, both a source of hydrogen and a sulphur recovery system are required. For these reasons, oil desulphurization units usually form part of an oil refinery, where the operation of such a unit can be combined with the operation of the refinery as a whole. Such an installation would produce fuel oil to meet specifications for a variety of applications, ranging from large utility installations to smaller scale applications. Typical costs of fuel oil desulphurization are given in Table 9.1.

9.4.2 Fuel Conversion Processes

Coal liquefaction processes will only be justified on practical and economic grounds if built on a large scale where the fuel that is produced can serve a multiplicity of installations. It is probable that fuel produced in this way may be substituted directly for residual fuel oils derived from crude oil. Liquefied coal is thus a possibility for use in both existing and new installations based on fuel oil.

Both coal and oil gasification may be done on a scale small enough to produce fuel for a single installation. Provided that the gasification step is oxygen based, the fuel gas produced could be substituted for coal or oil in existing installations. However, installations of this type are complex, involving in addition to the gasifier, an oxygen plant and sulphur recovery facilities. It remains to be seen how readily such installations will be accepted by the utility industry.

Fluidized bed gasification is suitable for large or small installations, and has the advantage that it is applicable to both new and existing installations. The spent lime produced is regenerable by oxidation to lime and sulphur dioxide, or alternatively the calcium sulphide may be converted to gypsum for eventual disposal. Sulphur dioxide in reasonable quantities can be used in industry.

No costs are presented here as it is felt that these methods are so indeterminate, particularly in the European situation, that any attempt to define costs at this stage would be misleading.

9.4.3 Combustion Techniques

Modified combustion techniques offer considerable promise, and can be applied to almost any fuel. In addition nitrogen oxides can be reduced at low costs by these techniques. They are, however, only suitable for new units, and then only on a reasonably large scale so that the economic benefits of increased size may be obtained.

9.4.4 Flue Gas Desulphurization

The technique of flue gas desulphurization may be applied to almost any boiler or power plant, provided that the physical space necessary for the installation of the desulphurization equipment is available. It is probable, however, that flue gas

Table 9.2 Typical Cost of Flue Gas Desulphurization Processes

Type of Process	Throwaway			Regenerative		
Unit capacity (MW)	100	500	1000	100	500	1000
Capital cost ($\$ \times 10^6$)						
New unit	18	52	82	36	104	168
Retrofit	25	73	123	50	146	246
Production Cost (mils/kW h)						
New unit						
Capital charges	6.8	3.9	3.1	13.6	7.8	6.2
Operation	2.0	2.0	2.0	3.4	3.4	3.4
Total	8.8	5.9	5.1	17.0	11.2	9.6
Retrofit						
Capital charges	9.4	5.5	4.6	18.4	11.0	9.2
Operation	2.0	2.0	2.0	3.4	3.4	3.4
Total	11.4	7.5	6.6	21.8	14.4	12.6

Basis: (1) coal fuel, 90% of sulphur removal; (2) 7000 hours/year operation, equivalent to 4500 hours peak load; (3) capital charge 17%, including maintenance; (4) all costs in 1978 dollars.

desulphurization will only be applied to installations of reasonable capacity, in order to obtain the benefits of scale on cost.

The question of waste disposal is of fundamental importance in selecting the type of flue gas desulphurization system to be employed. The throwaway system based on lime or limestone, must have a means of disposing of the waste sludge over the lifetime of the unit. This requirement will probably limit the application of such systems in many urban areas. The typical cost of flue gas desulphurization processes is given in Table 9.2.

9.5 CONCLUDING REMARKS

The first international convention on transboundary air pollution was signed in mid-November, 1979, in Geneva within the framework of the United Nations Economic Commission for Europe (ECE). It is a step forward that the problems of long range transport of air pollution have been recognized by all ECE countries. The member countries have not, however, been able to agree on a programme to reduce the emissions of sulphur dioxide. It is stated in the convention that the parties shall

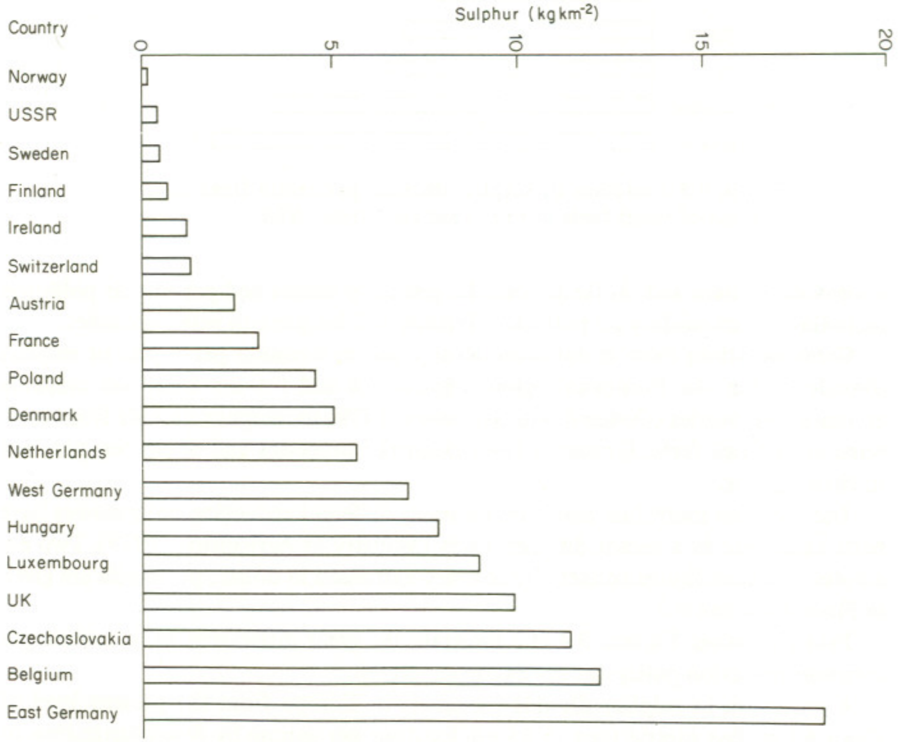

Figure 9.4 Emission density of sulphur dioxide from combustion of fossil fuels in European countries 1978

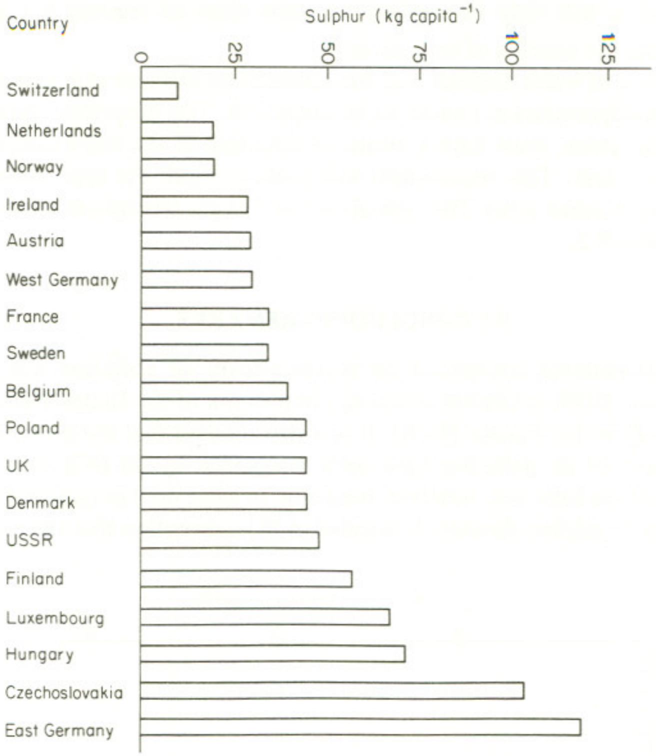

Figure 9.5 Emission of sulphur dioxide per capita from combustion of fossil fuels in European countries 1978

endeavour to limit and, as far as possible, gradually reduce and prevent air pollution including transboundary air pollution. Priority will be given to sulphur oxides.

Great variations exist in emission density and in emission per capita of sulphur dioxide within the European region. Figures 9.4 and 9.5 are based on available emission inventories (Dovland and Saltbones, 1979) for sulphur dioxide from combustion of fossil fuels. Emissions from industrial processes add about ten per cent to these figures.

The costs for individual countries assuming different reduction programmes have been calculated in a recent Swedish study (Ministry of Agriculture, 1979). Two examples of expenditures country by country expressed in dollars per capita are given in Figures 9.6 and 9.7.

Taken together Figures 9.4–9.7 illustrate the great difficulties in formulating a common reduction policy for the European region.

A reduction in sulphur dioxide emissions in Europe from the present level of about 60 million metric tons to 25 million tons per annum by desulphurization of fuels and stack gases would cost at least US $10 billion annually (1978 dollar). It is

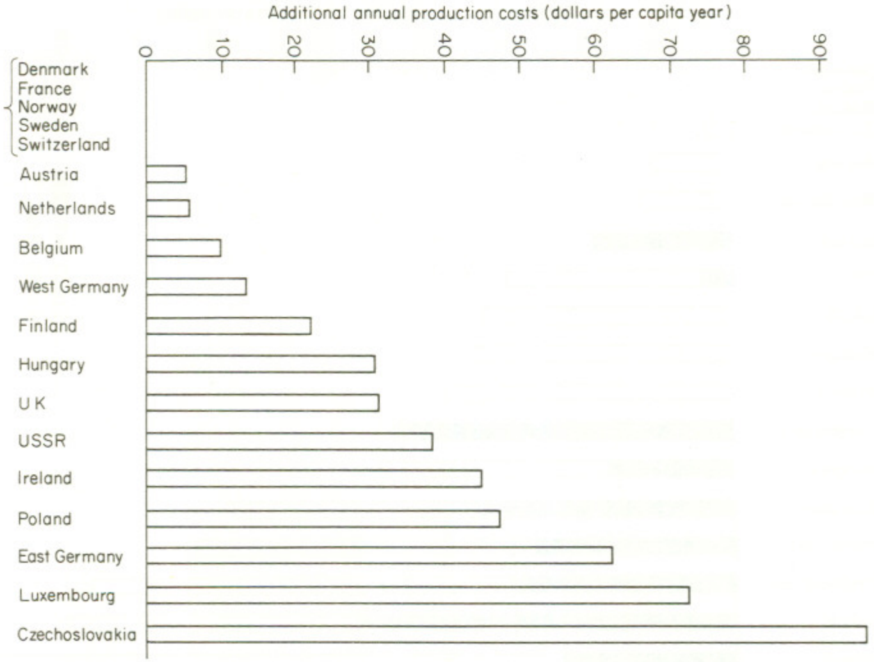

Figure 9.6 Annual costs in European countries to reduce 1990 emissions to 25 kg S per capita by a combination of fuel oil desulphurization and flue gas desulphurization in some coal fired installations

an enormous amount of money. However, if the costs of desulphurization of heavy fuel oil (Table 9.1) are related to the costs of fuel oil, and the costs of fuel gas desulphurization (Table 9.2) to the costs of electricity production the increases are about 10 and 15 per cent, respectively. Additional costs in the range of 10–15 per cent give another perspective of the expenditures involved especially in the light of a 300 per cent increase in oil prices in recent years.

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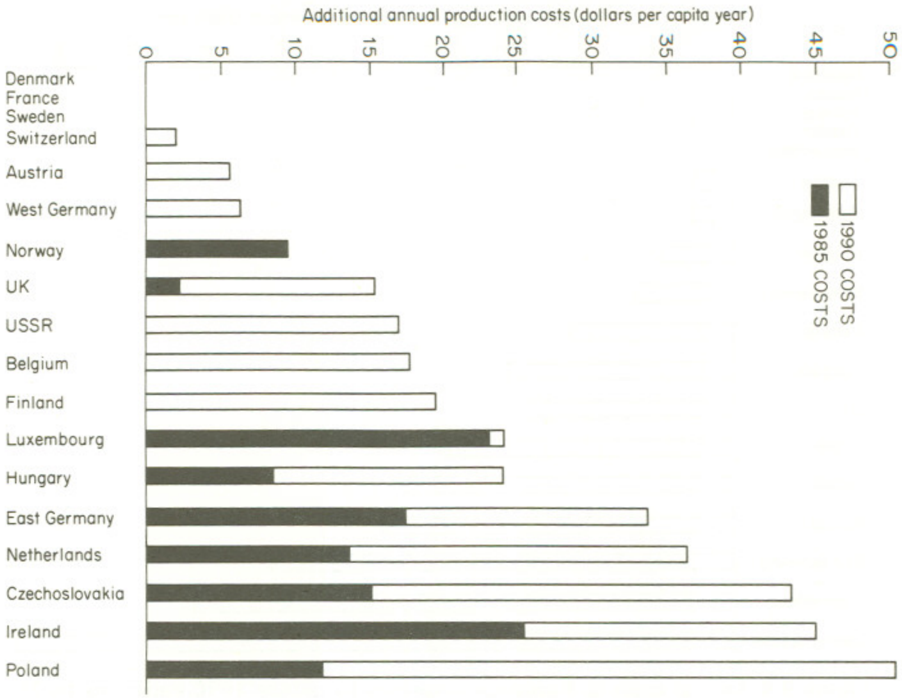

Figure 9.7 Annual costs in European countries to reduce 1985 emissions to equal 1975 levels (filled columns) and to reduce 1990 emissions by 25 % from the 1975 levels using a combination of fuel oil desulphurization and flue gas desulphurization in some coal fired installations

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