COSTS AND EFFECTIVENESS OF MEASURES TO REDUCE SO_2-EMISSIONS

A decision support analysis

R. FRIEDRICH, E. RUFF, A. VOSS
Institut für Kernenergetik und
Energiesysteme,
Universität Stuttgart,
Stuttgart,
Federal Republic of Germany

Abstract

COSTS AND EFFECTIVENESS OF MEASURES TO REDUCE SO_2-EMISSIONS: A DECISION SUPPORT ANALYSIS.

The damage to forests observed in the central and southern parts of the Federal Republic of Germany has increased very rapidly over the past two years. Most scientists believe that SO_2- and NO_x-emissions are the main reasons for this damage. This demands the immediate initiation of countermeasures. Since the benefits of these measures cannot be calculated exactly, political decisions have to be made under conditions that are uncertain. The paper demonstrates how and to what extent a cost-effectiveness analysis is able to support a rational decision process under these circumstances. The investigation area is Baden-Württemberg, a state situated in the south-west of the Federal Republic of Germany. First, a reference scenario is defined which describes the possible development of the electricity supply system. Then measures to reduce SO_2-emissions are collected and described. Measures required by law (for instance, installation of flue-gas desulphurization by July 1988), are not considered, since they are part of the reference scenario. A cost-effectiveness ratio – that is the amount of money needed to reduce the emissions by one kilogram of SO_2 – is evaluated for every measure considered. Measures with a cost-effectiveness ratio that is lower than or equal to that of measures required by law are recommended. Regional electricity suppliers have agreed to put these measures into effect. Realization of these measures will reduce SO_2-emissions in Baden-Württemberg by approximately 25%, or 19 000 t SO_2 per year, during the period 1984 to 1988. Experience shows that a carefully executed cost-effectiveness analysis can be a valuable input to a decision making process in an uncertain environment by evaluating and ranking the costs and effects of the SO_2-reduction measures that are at our disposal.

1. INTRODUCTION

The damage to forests observed in the central and southern parts of the Federal Republic of Germany has increased very rapidly over the past two years. The latest survey shows that more than one third of the total forests is seriously damaged. Most scientists believe that SO_2- and NO_x-emissions are the main reasons for this damage. However, the connection between SO_2- and NO_x-emissions and forest damage has not been proved, nor is the relative importance of other factors known;

the mechanisms involved are also not understood. Nevertheless, the vast damage demands the immediate initiation of countermeasures. Furthermore, acid rain caused by SO_2- and NO_x-emissions is responsible for the acidity of lakes and soil, damage to buildings, endangering of human health, etc.

Thus, a working group, initiated by the local government of Baden-Württemberg (a state situated in the southwest of the Federal Republic of Germany), was set up. It consisted of local government officials, directors of the regional electric power companies and scientists whose task it was to recommend strategies towards reducing SO_2-emissions from public power plants. The authors of this paper carried out the necessary analysis to support the working group.

Approximately 40% of the total SO_2-emissions in Baden-Württemberg emanate from public power plants. Restriction of the analysis to SO_2 and power plants was made to achieve rapid results. As the number of power plants in the state is small, they can be easily surveyed. Of even greater importance is the good relationship between the local government and the power companies, which enables the swift execution of countermeasures.

2. APPLIED METHODS

A direct quantitative connection between emissions and damage cannot be established. For example, no reliable spreading models exist for areas in the range of 40–1000 km, which is the distance over which forest damage and acidity of lakes occurs. However, even if the contribution of emissions to wet and dry depositions were known, the damage could not be quantified, because the quantitative relationship between deposition and damage is not known.

Thus, decisions have to be made under conditions that are uncertain. Futhermore, a complete cost-benefit analysis cannot be made, since the benefits, for example the area of less damaged forest or the longer lifetime of historical statues, cannot be quantified. However, as political decisions are required in this matter, a proper method to reach rational solutions has to be sought. This could be done by a cost-effectiveness analysis that evaluates the costs of measures to reduce SO_2-emissions and their effectiveness, the latter being the extent of reduction of SO_2-emissions.

First a reference scenario is set up which defines the possible development of power plant use and the resulting SO_2-emissions. Then, the various measures to reduce SO_2-emissions are identified. Subsequently, starting from the reference scenario, the surplus costs and SO_2-emissions avoided for every measure are calculated. These two values are computed, time-dependent for every year from 1984 to 1995. To calculate the costs, a dynamic economic analysis is made. The annual costs are then converted to a net cash value.

Avoidance of emissions in the near future is more valuable than in the far future because

– emissions cause damage, which can theoretically be converted to costs, so emissions can thus be treated as costs
– the emission level decreases with time after 1988 because of existing environmental regulations, so it is more essential to reduce the emissions as soon as possible.

Thus emissions are also transformed into a net current value by means of the real interest rate; the quotient of the two values is the cost-effectiveness ratio.

Since uncertainty exists of the benefits in monetary terms of a certain effectiveness value, the decision concerning which cost-effectiveness ratio should be accepted is a political and not a scientific one. However, there are certain indications that some measures, especially flue-gas desulphurization, have already been accepted politically. Therefore, if a measure has the same or better cost-effectiveness ratio than flue-gas desulphurization it can certainly be recommended, provided no other disadvantages occur.

Of course, other criteria do exist that could prevent the recommendation of measures, one being the sensitivity of the cost-effectiveness ratio to changes in the assumptions, especially to changes in future electricity demands. Thus, a sensitivity analysis has to be made.

Only if the cost-effectiveness ratio remains under a certain limit for a wide range of assumptions can the measure be recommended.

Other advantages or disadvantages of measures, such as lower or higher emissions of other pollutants or the effects on places of employment, also have to be considered.

Another investigation that has to be made is to ascertain the influence of different measures carried out simultaneously. For this purpose the successive execution of measures is simulated, starting with the measure of the best cost-effectiveness ratio. The result is a trade-off curve between surplus cost and reduced emissions. The cost-effectiveness ratios resulting from this calculation are used for decision making. They are a little higher than those reached by the execution of one single measure alone, but this investigation involves no alteration of the sequence of measures.

Often another difficulty occurs when such an analysis is performed, i.e. the difficulty of achieving results. The best cost-effectiveness ratio is not sufficient when the measure is not acceptable or cannot be carried out. This problem has been solved in the following manner. During the decision-making process the results of analyses were presented in discussion meetings with representatives of the electric power industry and the local government. Through the steady feedback system, various interests and opinions were taken into account and adapted to suit each party. Thus, common acceptance towards the realization of certain measures to reduce SO_2-emissions was reached.

This proved to be of great help because the cost-effectiveness ratio was easily understood by all. With more sophisticated methods, the relationship between concrete action and results would probably not have been as quickly understood, thus resulting in less acceptance of these measures. As the companies were directly involved, they accepted the results and guaranteed to carry out the recommended measures.

3. CONSTRAINTS OF THE PUBLIC ELECTRICITY PRODUCTION SYSTEM IN BADEN-WÜRTTEMBERG

To be able to assess sensibly any measure to reduce SO_2-emissions in Baden-Württemberg (BW), a basic postulation must be made of electricity production and SO_2-emissions, i.e. a reference scenario. This must assess the annual production of each power plant and the expected SO_2-emissions from 1980 to 1995. The basic assumptions of this reference scenario are:

(a) The average increase rate of electricity consumption in BW is 3%/a. This assumption of growth rate is not a prognosis of the future, but is a necessary means to provide quantitative conclusions. Sensitivity analyses, which deal with the effects of changed growth rates on results, are made subsequently.
(b) According to arrangements between public electricity suppliers and the coal mining industry, a fixed and increasing amount of Federal German hard coal must be used in power plants until 1995.
(c) Existing environmental laws have to be fulfilled, particularly the Großfeuer-anlagenverordnung (GfVO).

Figure 1 shows the development of public electricity production in BW, differentiated into energy sources.

The electricity production of nuclear power plants will rise from a currently 23% to over 50% by 1995.

The capacity of coal-fired power plants will increase steadily in the future as more than 2500 MW(e) are installed. Because of this, about 330 MW(e) will be closed down and about 1250 MW(e) will move from continuous into sporadic reserve production.

A structural change will occur in late 1984 when the present electricity import contracts end.

Therefore, there will be a strong increase in electricity production in BW. Subsequently, an increasing amount of coal will have to be fired, from 3.9 million tonnes in 1984 to 6.2 million tonnes in 1989. Despite the increase in use of hard coal up to 1989, a hard coal stockpile of more than 3 million tonnes will still remain after 1995.

Federal German environmental regulations, e.g. the GfVO, stipulate that flue-gas desulphurization plants must be installed in existing power plants by July 1988. Since use of hard coal will rise considerably by 1988, so will SO_2-emissions provided that no additional measures be taken. These high SO_2-emissions

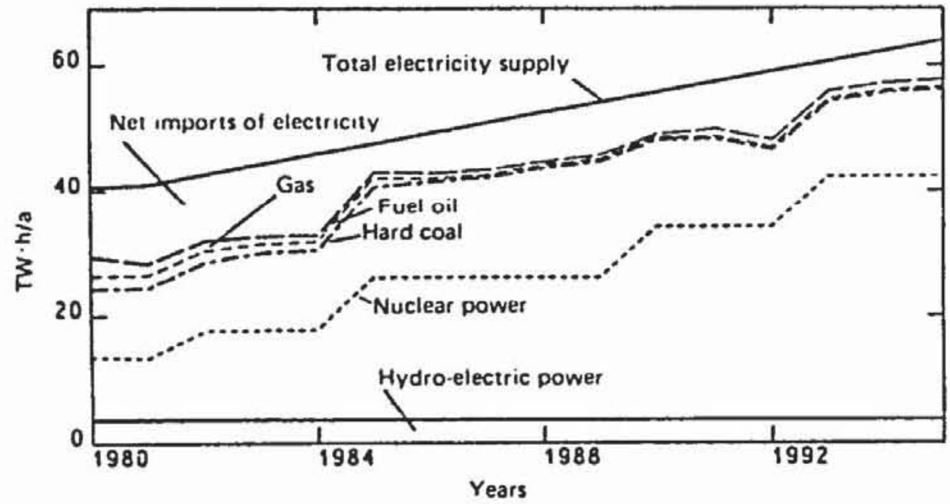

FIG.1. Electricity production of public power plants in Baden-Württemberg.

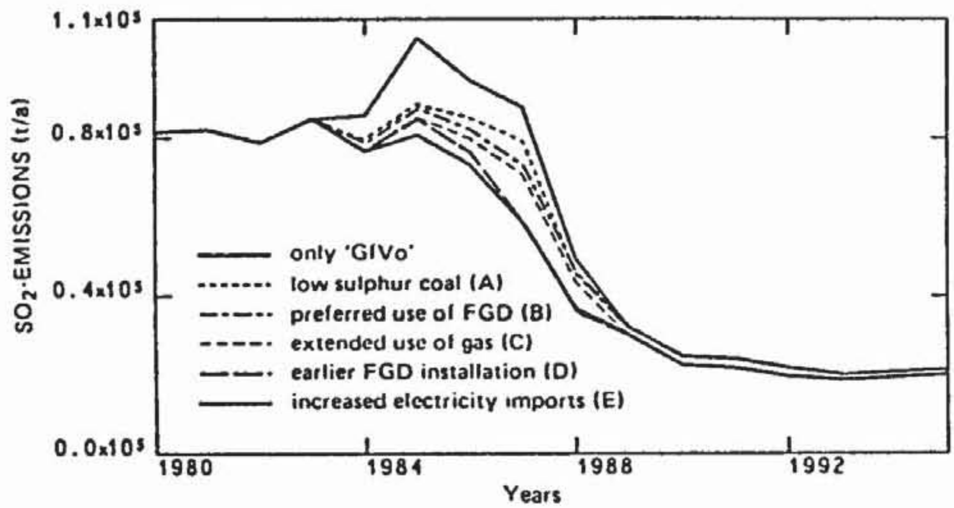

FIG.2. Reduction of SO_2-emissions by different measures.

are shown in Fig.2 (top line 'only GfVO'). The growth rate of SO_2-emissions is less than that of hard coal because power plants now under construction have flue-gas desulphurization for one half of the flue gas at start-up. Large-scale installation of flue-gas desulphurization plants by 1988 will then reduce the SO_2-emissions to about 25% of the present value.

These results show clearly that the increase in SO_2-emissions over the next few years is the real issue, whereas in the long run SO_2-emissions will be drastically reduced by existing environmental regulations.

Thus, the main task was to find measures that reduce the emissions rapidly (from 1984–1988) and that have cost-effectiveness ratios that are equal to, or better than, those of an ordinary flue-gas desulphurization plant (about 3–6 DM/kg SO_2).

4. RECOMMENDED MEASURES TO REDUCE SO_2-EMISSIONS

A number of measures to reduce SO_2-emissions were identified and analysed for their cost and effectiveness. Only those measures that have a favourable cost-effectiveness ratio will be presented here. They are recommended in addition to existing environmental laws and have been accepted by the electric power companies. A successive realization of each of the five measures (A-E) reduces SO_2-emissions, as shown in Fig.2.

4.1. Measure A: Optimized use of low sulphurous coal

SO_2-emissions are directly proportional to the amount of sulphur in the coal used. Ordinary Federal German hard coal contains about 0.91 – 0.95% sulphur, but domestic hard coals are available that are less sulphurous (e.g. 0.85%). Far less sulphurous coals are obtainable from South Africa, Canada, Australia and the USA; they only contain 0.35 to 0.55% sulphur. Nevertheless, the possibilities of using imported coal are restricted, because an agreement between the Federal German electric power companies and the Federal German coal mining industry exists to use a fixed amount of domestic hard coal until the year 1995. Furthermore, some energy suppliers have fixed contracts to import certain quantities. Thus, the additional amount of import coal with a low sulphur content remains small; it amounts to only 5% of the entire coal that will be used from 1985 – 1990 and 2.3% for the next five years.

An additional way of reducing SO_2- emissions is to burn a great deal of low sulphurous hard coals in power plants that have not yet been retrofitted with flue-gas desulphurization. To calculate the SO_2-reduction effect, it is assumed that – without the measures mentioned above – the average sulphur content would be 0.95%. On this assumption, the reduction of SO_2-emissions through optimized use of low sulphurous hard coals amounts to approximately 35 400 tonnes of SO_2 from 1984 to 1988.

As the current price of low sulphurous coals does not exceed the price of other import coals, this measure involves at present no additional costs. Of course, this price ratio may change in the future if the demand for low sulphur coal rises.

4.2. Measure B: Preferred use of power plants with flue-gas desulphurization plants

There are three hard coal power plants now under construction. All have 50% of their flue gas treated by desulphurization plants in a first step. Another hard coal power plant with 50% desulphurization is already in use. To reduce SO_2-emissions, a change in operation could be made in that plants using part-treated flue gas would be preferred to other plants. This would not be economically optimal but would contribute to less SO_2-emission. A rough calculation of this effect points to about 12 000 tonnes of SO_2-reduction from 1984 to 1988: This measure will cost about 0.15 Pf/kW(e)·h or 0.5 DM/kg SO_2.

4.3. Measure C: Extended use of natural gas

Some power plants are able to use more than one fuel (mostly natural gas and heavy fuel oil). They could be operated by using more natural gas, which has almost no sulphur, in place of oil. However, there are restrictions to this substitution. The availability of natural gas and the capacity of gas-fired power plants must be taken into account. Thus, SO_2-emissions could be reduced by about 25 200 t SO_2 by 1995 or about 2300 t SO_2 per year. This substitution costs 1.7 DM/kg SO_2.

4.4. Measure D: Earlier installation of flue-gas desulphurization plants than demanded by law

According to Federal German environmental law, all power plants with more than 300 MW(th) and an expected operating time of more than 30 000 hours from July 1984 onwards must be retrofitted with flue-gas desulphurization plants by July 1988. Regarding power plants now under construction flue-gas desulphurization must be partly installed before 1988. Despite the relatively long construction time of these plants, it may be possible to complete them earlier so that they can be used earlier than intended.

This measure will reduce the SO_2-emission by 24 000 t from 1984 to 1988 and will result in additional costs of about 3 DM/kg SO_2.

4.5. Measure E: Enlarged electricity imports

There is a possibility of enlarging the electricity import from abroad for the years 1986 and 1987 and to export the same amount of electricity in the years after 1988. This means that because of imports, power plants with SO_2-emissions will be less used and, thus, SO_2-emissions will be reduced in 1985 and 1986. After the power plants' retrofit, re-exporting can be made by emitting only one fifth of the SO_2-emissions that would occur before 1988.

The effect on the SO_2-emissions of all the measures discussed is shown in Fig.2. If all the measures are realized, SO_2-emissions can be reduced by 25% from 1984 to 1986, or by 18 800 t of SO_2 per year up to 1986, with additional costs of 18 million DM/a.

5. OTHER MEASURES

Apart from the measures discussed, a number of additional measures were analysed. However, they were either unsatisfactory regarding their cost-effectiveness ratio, or were technically not feasible, or had to be given up because they did not correspond to existing laws or social aims. Some of these measures are briefly discussed.

SO_2-emissions from public power plants may be reduced by using still more low sulphurous hard coal. This can be realized in two ways:

- lowering the content of sulphur in hard coal through hard coal desulphurization
- using more imported low sulphurous coal.

All Federal German hard coals are treated in order to lower the sulphur content. Using measures such as flotation, only sulphur that is not organically bound can be removed; about 0.7–0.8% of the organically bound sulphur remains.

At present, enhanced desulphurization of hard coal is not possible. Since an important analysis constraint is to ensure that a fixed amount of domestic coal is used, the possibility of firing still more imported low sulphurous coal is limited to that amount of hard coal that remains if the cumulated domestic input is subtracted from the total coal use. To augment the effect on the reduction of SO_2-emissions, low sulphurous coals that are planned to be used in the years after 1988 are shifted to the time period 1984 to 1988. During this period, coal fired power plants that have not yet been retrofitted will burn these low sulphurous coals. After 1988, when these power plants are retrofitted, the more sulphurous Federal German coal which so far will have been stockpiled will be burnt.

This will lead to a reduction of SO_2-emissions by 1988 and will decrease SO_2-emissions considerably afterwards. However, as the quantities of low sulphurous coal to be shifted are very small, the effect on SO_2-emissions will be limited to about 6700 t of SO_2 from 1981–1986. The cost-effectiveness ratio of this measure amounts to 13 DM/kg SO_2, which is far more than that of the flue-gas desulphurization plants (3–6 DM/kg SO_2). Another problem is that the quantity of coal that can be shifted depends on the growth of electricity consumption. Given an average rate of less than 3%, the amount of Federal German coal that has been held back will not be able to be used up after 1988.

Another way of reducing SO_2-emissions is to use more fuels with little or no sulphur.

The output of nuclear power plants cannot increase as they are already being run at full capacity. Fuel oils cannot be considered because of their high sulphur content, insufficient capacity and high prices. Greater use of natural gas remains. In a similar way to the previous measure, only limited quantities of gas could be substituted for hard coal. As gas contains almost no sulphur, the effect on SO_2-emissions is more positive. However, storage expenses and the higher than coal price contribute to costs of about 260 million DM and a ratio of 16 DM per kg SO_2 not released. The total reduction of SO_2-emission amounts to 16 200 t of SO_2 from 1984 to 1987.

Only by giving up the constraint of using a fixed quantity of Federal German coal (and using gas or low sulphurous import coal instead) would a large reduction of SO_2-emission of about 60 000 t of SO_2 by 1988 be possible. The resulting problems, especially for the domestic coal mining industry, were not within the scope of the analyses.

Finally, the measure to retrofit far more power plants with flue-gas desulphurization than required by present regulations is analysed. These power plants are reserve plants, that are operated only for about 100–500 hours per year.

To retrofit these power plants would cause installation costs of 280 million DM and reduce SO_2-emissions only by 1700 t of SO_2 per year after 1988. The cost-effectiveness ratio of this measure, being 42 DM/kg SO_2, is by far the worst.

6. SENSITIVITY OF RESULTS OF DIFFERENT ELECTRICITY CONSUMPTION GROWTH RATES

The assumption of a 3% electricity consumption growth rate is not a prognosis or forecast of actual future development. Therefore, a comprehensive analysis must deal with higher and lower growth rates than 3%.

If the growth rate of electricity consumption exceeded 3% per year, electricity production and SO_2-emissions by coal-fired power plants would also increase. As nuclear power plants are operated at full capacity and oil and fuel oil cost much more than coal, additional production will be carried out in coal fired plants. Before 1988, when some plants will not as yet have been retrofitted with desulphurization plants, there will be a higher demand for electricity, which would therefore result in an increase of SO_2-emissions.

If the electricity consumption growth rate is less than 3%, the fixed quantities of Federal German hard coal forced to be fired will limit the reduction in SO_2-emissions.

This means that with a lower demand for electricity use of coal can only be reduced to a certain degree, resulting in only slightly reduced SO_2-emissions. A lower electricity growth rate of 2%/a would only reduce SO_2-emissions by 5%.

Therefore, considering different electricity consumption growth rates, the tendency of SO_2-emissions of public power plants remains unchanged and does not affect the conclusions and recommendations based on the cost-effectiveness analysis discussed in previous sections.

7. SUMMARY

The damage caused by specific air pollutants cannot be quantified because the meteorological and ecological sciences are not yet able to produce quantitative equations for the relationship between emissions and damage.

This means that decisions to reduce air pollutant emissions, for example SO_2-emissions, have to be made under conditions that are uncertain. As the benefit of a measure to reduce SO_2-emissions cannot be assessed in a direct way, one has to substitute the reduction of emissions caused by a measure. This can be done by a comparison of the level of emissions in a reference case to the level of emissions after the measure has been realized. The difference corresponds to the effectiveness of every measure. After evaluating the costs of every measure and its effectiveness by a cost-effectiveness analysis, every measure can be valued by its specific cost-effectiveness ratio. This ratio ranks the various measures. Furthermore, it can also help to determine where best the priorities in research effort should lie.

A cost-effectiveness analysis was made for the emissions of power plants in Baden-Württemberg. Flue-gas desulphurization plants will be installed in the power plants with medium and high utilization by 1988. However, before 1988 the SO_2-emissions in Baden-Württemberg would rise considerably if no counter-measures were undertaken.

Thus, the measures to reduce SO_2-emissions in the short term, i.e. before 1988, had to be identified and analysed.

Measures with cost-effectiveness ratios equal to, or better than, that of flue-gas desulphurization plants were identified and recommended by detailed cost-effectiveness analyses. These are:

(a) Use of more low sulphurous hard coal, especially in power plants that have as yet not been retrofitted with flue-gas desulphurization.
(b) Preferred use of power plants that have flue-gas desulphurization plants, or at least realized the first steps, to plants without flue-gas desulphurization.
(c) Extended use of natural gas in mixed fuelled plants.
(d) Earlier starting operations of flue-gas desulphurization plants than demanded by law.
(e) Use of further possibilities to import electricity and re-export of the same amount of electricity later from power plants with flue-gas desulphurization.

The effect of the recommended measures would be a reduction of SO_2-emissions from public power plants in Baden-Württemberg of about 25% of the current value or 18 800 t of SO_2 per year from 1984–1986.

Summarizing the main results, Fig.3 shows the trade-offs of additional costs and measures to reduce SO_2-emissions.

As measure (E) cannot be assessed because of a lack of the estimated costs, only four recommended measures are shown, together with the unfavourable measures. These are an advanced use of import coal (F) and natural gas (G) and an additional installation of flue-gas desulphurization in power plants only used as standby-plants (H). The two curves shown in Fig.3 are the measures (F) and (G), which cannot be implemented together.

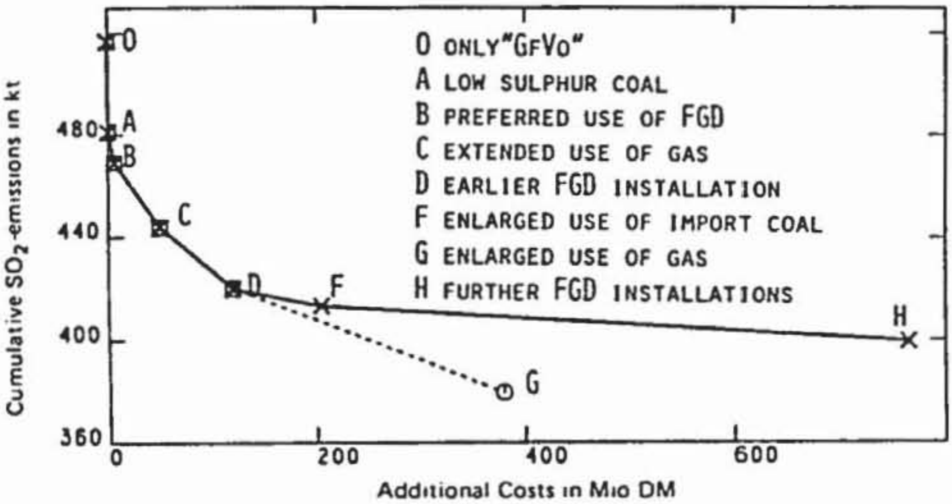

FIG. 3. Trade-off between SO_2-emissions and additional costs.

It should be noted that the results and recommendations drawn from the cost-effectiveness analysis only apply to Baden-Württemberg. For other regions or altered constraints, other results and recommendations would apply. However, cost-effectiveness analysis could be transferred to other situations.

The practical experience gained by carrying out the investigations shows that a cost-effectiveness analysis is able to provide useful information for assessing the various measures to reduce SO_2-emissions, although uncertainty exists on the causal connections between pollutants and damage. Furthermore, the cost-effectiveness analysis proves to be a helpful instrument to de-emotionalize the difficult discussions between the power industry which has to fulfil environmental regulations and politicians who are responsible for environmental affairs. Thereby, the method contributes to rational and sensible decision making.

The method is especially suitable for finding measures that consider the special conditions and circumstances of the electricity supply system. In contrast to inflexible rules such as fixed emission standards, the measures consider each particular existing structure in a flexible way. Therefore, an optimal solution regarding costs and effects will be found.