# COST-OPTIMAL EMISSION CONTROL STRATEGIES - RESULTS OF A COMPREHENSIVE COST-EFFECTIVENESS ANALYSIS FOR REDUCING AIR POLLUTION FROM MULTIPLE SOURCES

by

A. VOSS, B. BOYSEN, R. FRIEDRICH, M. MATTIS
Institut für Kernenergetik und Energiesysteme
University of Stuttgart
Pfaffenwaldring 31
D-7000 Stuttgart 80
Federal Republic of Germany

## I. INTRODUCTION

The observed and increasing damages to forests in central and south Germany have created a great public concern and have put tremendous pressure on the policy makers to drastically reduce air pollutants as the likely cause of the damage.

Initially $SO_2$ was assumed to be the main cause of damage. Recently however, photochemic oxidants developed from nitrogen oxides and hydrocarbons under the influence of sunlight, have gained greater attention as one of the likely causes of tree damage.

Although there is some evidence that air pollution contributes to the observed damages, the connections between $SO_2$- and $NO_x$-emissions and forest damage are not proven yet, nor is the relative importance of other factors known and are the complex mechanisms involved fully understood.

Because of the existing scientific uncertainties and the emotions involved, rational policy making related to air quality control is particularly difficult. Costs and investments of billions of DM are at stake and stricter environmental regulations might have a profound impact on the energy sector and specific energy industries. Usually one would base one's decision on the controls to be taken and their optimal timephasing to reduce air pollution from different sources on a detailed cost-benefit analysis, which weighs the advantages and disadvantages of any course of action.

Due to the uncertainties involved and without any knowledge of the acceptable level of emissions from an ecological point of view, it seems to be obvious that a full scale cost-benefit analysis of alternative emission control strategies cannot be performed as basis for a rational control policy. Thereby the most obvious difficulties stem from the unknown dose-response relationships for the relevant pollutants.

Since a cost-benefit analysis on the subject cannot be carried out because of informational difficulites, a cost-effectiveness approach for identifying the most rational course of action seems to be the appropriate tool. Based on a careful consideration of the costs and potential emission reductions of various control measures, the 'cost-effectiveness analysis' selects the most cost-effective combination from the many possibilities of environmental improvement methods aiming at the same target, e.g. the reduction of $SO_2$- and $NO_x$-emissions.

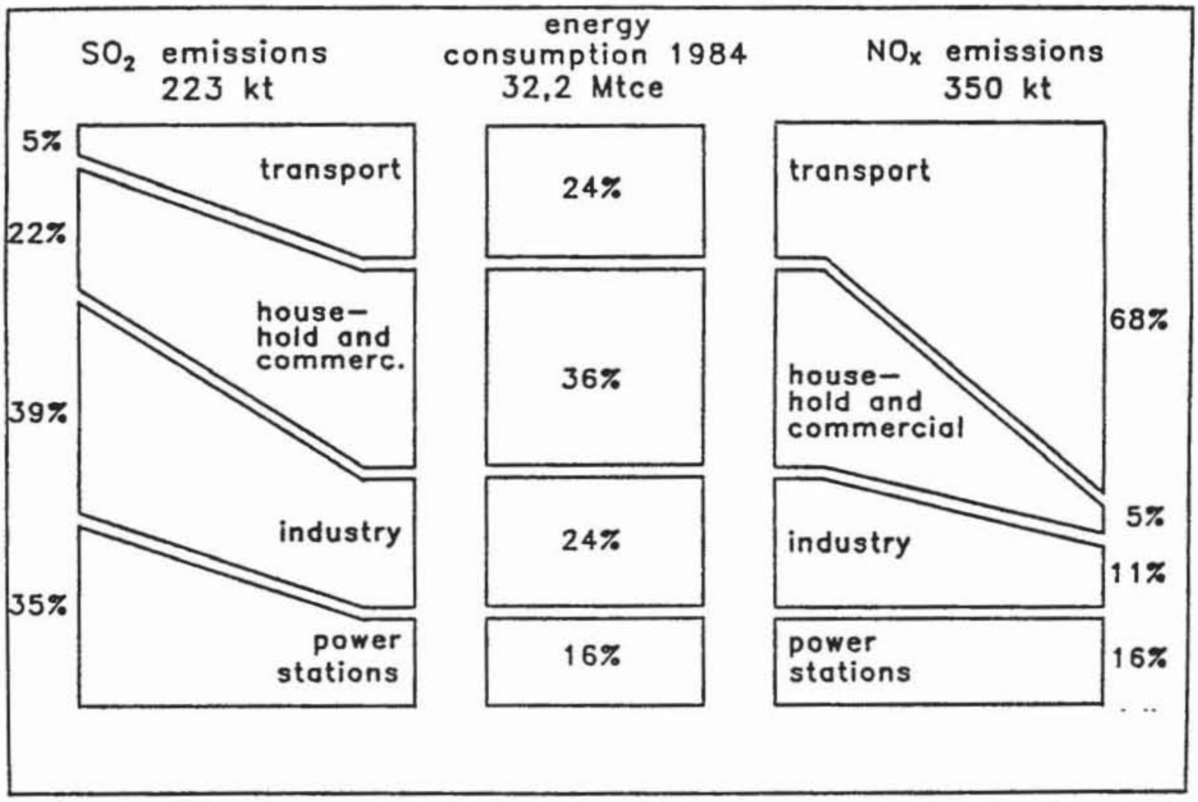
From a methodological point of view this approach is relatively straigthforward and the rational behind it is maximizing emission reduction while minimizing related control costs. The cost-effectiveness of a measure or control technique is usually expressed by the 'specific reduction costs' (SRC), being the ratio of control costs and the amount of emission reduced, e.g. DM/kg $SO_2$ removed, and the cost optimal control policy is determined by the ranking of alternative control measures according to their specific-reduction costs.

The cost-effectiveness approach, as discussed briefly above, was the basic tool used to analyse and identify an optimal control policy to reduce $SO_2$- and $NO_x$-emissions in Baden-Württemberg, a state located in the south-west of the Federal Republic of Germany. In the following we will discuss the major results of the analysis carried out so far. As work on some emission sectors is still in progress, some of the results presented must be considered as preliminary. A more extensive description of the findings can be found elsewhere [1,2,3,4].

## II. EMISSIONS AND THEIR CONTROL IN BADEN-WÜRTTEMBERG

Although natural sources contribute significantly to the global sulphur and nitrogen emissions, anthropogenic sources are the dominant factor in the industrialized countries. Figure 1 illustrates the actual situation concerning man-made sources of $SO_2$ and $NO_x$ in Baden-Württemberg.

Figure 1: Energy consumption and related $SO_2$- and $NO_x$-emissions in Baden-Württemberg (1984)




Current emissions of sulphur- and nitrogen oxides within Baden-Württemberg are estimated at 223 kt $SO_2$ and 350 kt $NO_x$ per year. The primary sources of $SO_2$ are the utilities and the industrial sector. Together they account for nearly three-quarters of the total $SO_2$-emissions. In contrast their contribution to the $NO_x$-emissions is only 27 %. The main source here is the transport sector contributing 68 % to the total emissions.

To be able to quantify the costs and effects of alternative emission control measures and strategies a 'reference scenario' was set up, describing the development of energy demand, fuel input and conversion or end-use technologies used in the different sectors as well as the resulting $SO_2$- and $NO_x$-emissions. Subsequently, starting from the reference scenario, the surplus costs and emissions avoided for every control measure were calculated over the time horizon 1984 to 1995.

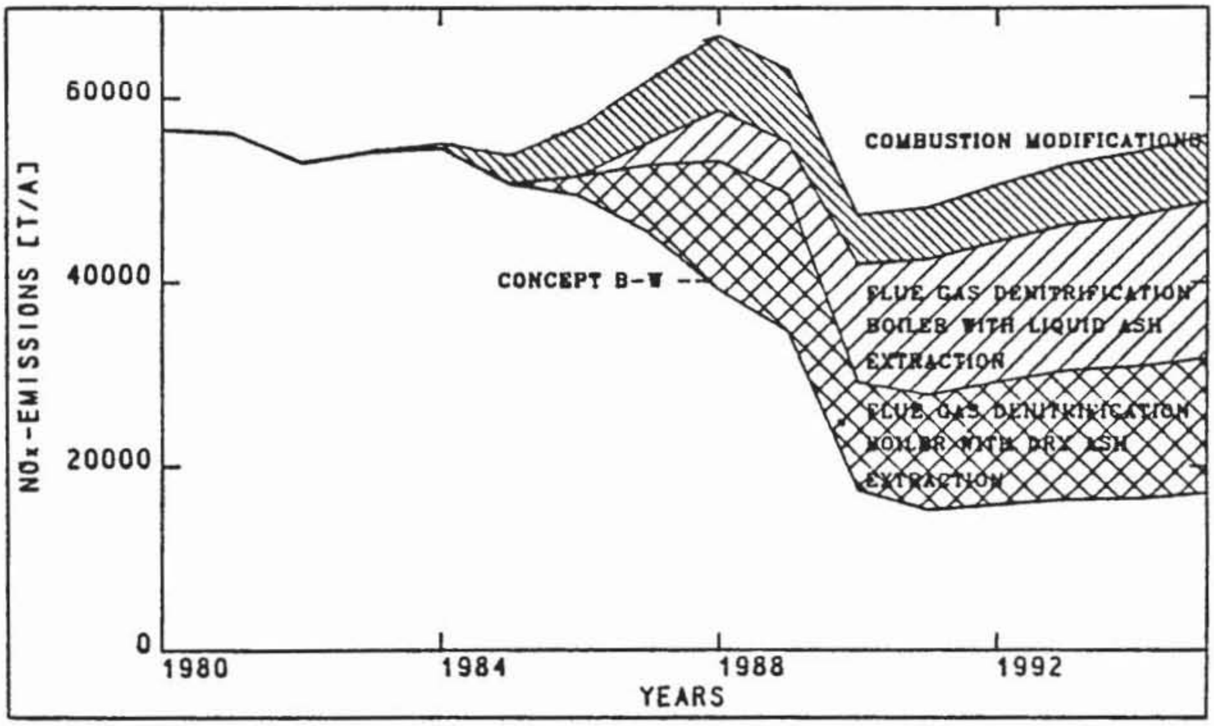
A broad variety of technical as well as fuel- and plant-management measures do exist to reduce $SO_2$- and $NO_x$-emissions from different sources. Abatement technologies are in different stages of development and application as well as control costs vary significantly depending on specific characteristics of the emitting device or process, such as size, type of technology, age, and operational limitations. This requires a detailed analysis, as far as possible on a plant by plant basis, of the appropriate control techniques and their associated costs (including plant specific retrofitting costs) for the different emission sources, as well as the analysis of fuel switching and fuel management measures.

For the large utility and industrial boilers (size >50 $MW_{th}$) the cost-effectiveness-investigation is based on an individual analysis of each boiler whereas for the plentiful small size sources in industry, in househould and commercial and in the transport sector typical representative figures had to be used. In the following some results for the different sectors will be discussed.

II.A Public Power Plants

Based on an average growth rate of 3 %/a total electricity supply in Baden-Württemberg will increase from 43 TWh/a to about 63 TWh/a in 1995. Although electricity production of nuclear plants will rise to nearly 60 % of the total by 1995, growing electricity consumption requires increasing electricity generation from coal power plants. Without any control measures $NO_x$-emissions would increase from 55 kt/a to 67 Kt/a in 1988 (see Figure 2). Reductions thereafter are a result of an increased nuclear production and a higher share of modern boilers with dry ash extraction, having lower specific $NO_x$-emissions than boilers with liquid ash extraction.

Figure 2: Reduction of $NO_x$-emissions by different measures




Combustion modification measures, including low $NO_x$-burners will reduce $NO_x$-emissions in the short run by nearly 15 %. Further drastic reductions of the emission level will be achieved by the installation of flue-gas denitrification facilities using the selective catalytic reduction (SCR) process. By the mid nineties $NO_x$-emissions will have dropped to about 17 kt/a or about 30 % of today's level. The drastically reduced emissions will be achieved even though the use of hard coal is increasing.

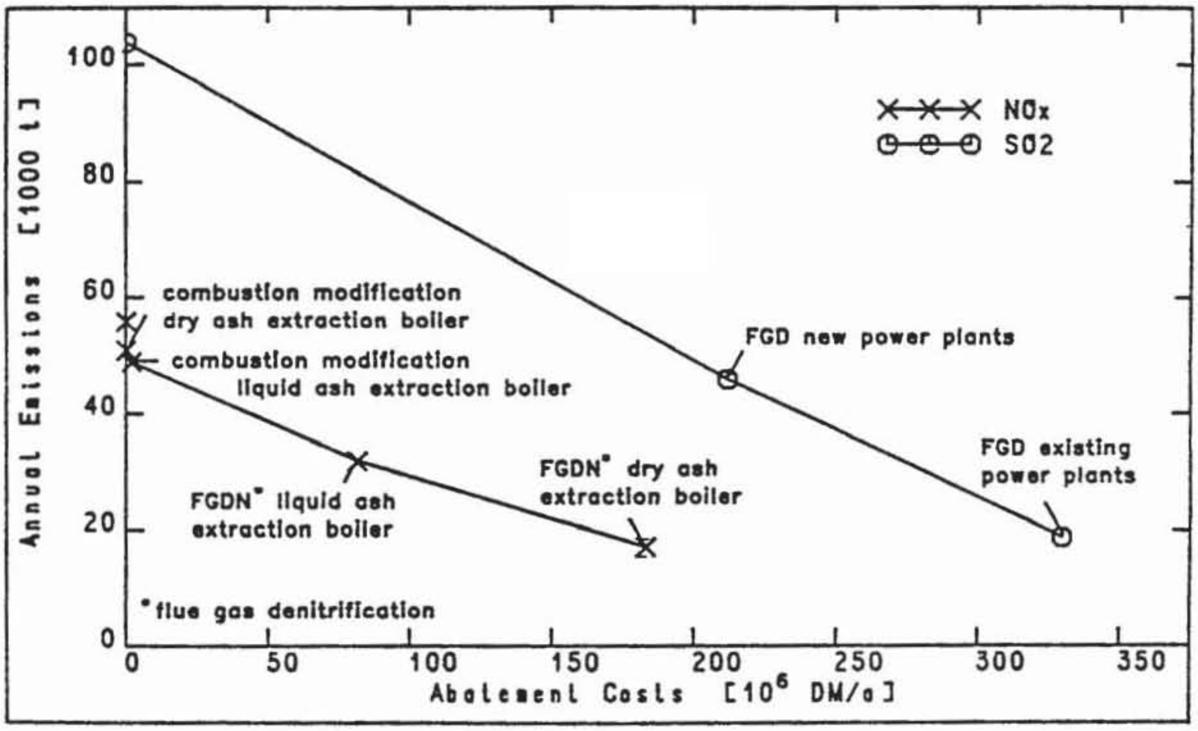
The cost effectiveness of the different categories of $NO_x$-reduction measures is given in Table 1. The specific reduction costs (SRC) of combustion modifications are very attractive (<1 DM/kg $NO_x$), but it must kept in mind, that their reduction potential is limited, so that strict emission standards (e.g. 200 mg $NO_x/m^3$) cannot be met. The specific reduction costs of flue gas denitrification depends to a great extend on the size of the plant, the boiler type and the load factor. In the case of the power plants in Baden-Württemberg they range from 3 to 8 DM/kg $NO_x$ removed. The mean value for boilers with liquid ash extraction being 4.6 DM/kg $NO_x$ and 6.9 DM/kg $NO_x$ for dry ash extraction boilers.

Table 1: $NO_x$-emission control in public power plants

| measure | emission level in 1995 [$10^3$ t] | abated emissions [$10^3$ t] | annual cost [$10^6$DM] | specific reduction cost (SRC) [DM/kg $NO_x$] |
|---|---|---|---|---|
| none | 55,86 | - | - | - |
| combustion modification: | | | | |
| dry ash extraction boilers | 50,93 | 4,93 | 0 | 0 |
| liquid ash extraction boilers | 48,9 | 2,03 | 1,95 | 0,96 |
| flue gas denitrification (FGDN): | | | | |
| liquid ash extraction boilers | 31,83 | 17,07 | 79,5 | 4,66 |
| dry ash extraction boiler | 17,1 | 14,73 | 101,5 | 6,89 |

Even more drastic reductions can be achieved in the case of $SO_2$-emissions. There are a set of measures in the area of fuel- and power plant management that could contribute to an immediate reduction of $SO_2$-emissions [1,5]. In the long run however drastic reduction can only be achieved by flue gas desulphurisation (FGD) processes. Figure 3 gives the cost curve of reducing $SO_2$-emissions in public power plants. The specific reduction costs of flue gas desulphurisation is in the range of 3 to 6 DM/kg $SO_2$ removed, depending on the plant size and the load factor. With flue gas desulphurisation the $SO_2$-emissions will drop from 104 kt to 19 kt per year in 1995, resulting in annual abatement costs of 330 Million DM.

Figure 3: Cost curves for the reduction of $SO_2$- and $NO_x$-emissions in public power plants




## II.B Industry

The reference projection of fuel consumption by industry in Baden-Württemberg, based on an average growth rate of industrial net-production of 2 %, is given in Figure 4. Due to the continuation of efforts for the rational use of energy, overall fuel consumption will continue to decrease slightly to about 210 PJ/a in 1995. The consumption of heavy-fuel oil will continue to decline, so that its share will decrease to only 20 % by

1995, compared to 40 % in 1982. The main substitute for heavy-fuel oil will be natural gas. This substitution will have a beneficial effect on both the $SO_2$- und $NO_x$-emissions from industry. In the reference case industrial $SO_2$-emissions will be reduced by about 30 % to 61 kt by the mid of the next decade. The corresponding figures for $NO_x$ are a reduction of only 8 % to 34 kt/a in 1995. The cost curves for the reduction of both $SO_2$- and $NO_x$-emissions in industrial firing installations for the year 1995 are given in Figure 5.

The new emission standards for firing installations of up to 50 $MW_{th}$ set by the 'Technical Guideline for Air Quality Control 1986' will result in a 7 % respectively 9 % reduction of the $SO_2$- and $NO_x$-emissions. Abatement costs are in the range of 30 Million DM per year, because standards can by met by primary measures in the case of $NO_x$ and by using low-sulphur fuels in the case of $SO_2$. Further controls of both emissions are possible but they are less cost-effective.

Overall cost of flue-gas treatment techniques are depending on the type, size and capacity factor of the boiler, the specific retrofitting situation as well as on the waste disposal or utilisation cost [3]. Because of this site-specific nature of these control costs the marginal specific reduction costs of flue-gas treating processes have been used to determine the emission reduction cost curves in industry. As it can be seen from Figure 5, a reduction of the $SO_2$-emissions in the order of 8 kt/a could be achieved through the installation of flue-gas desulphurisation facilties with specific reduction costs lower than 5 DM/kg $SO_2$. As far as the $SO_2$-emissions are concerned the desulphurisation of light fuel oil and the substitution of heavy fuel oil in refineries by natural gas could contribute to a further decrease of this pollutant. Thereby the extended use of natural gas in refineries will have also a positive effect on the $NO_x$-emissions.

Figure 4: Fuel consumption by industry in Baden-Württemberg

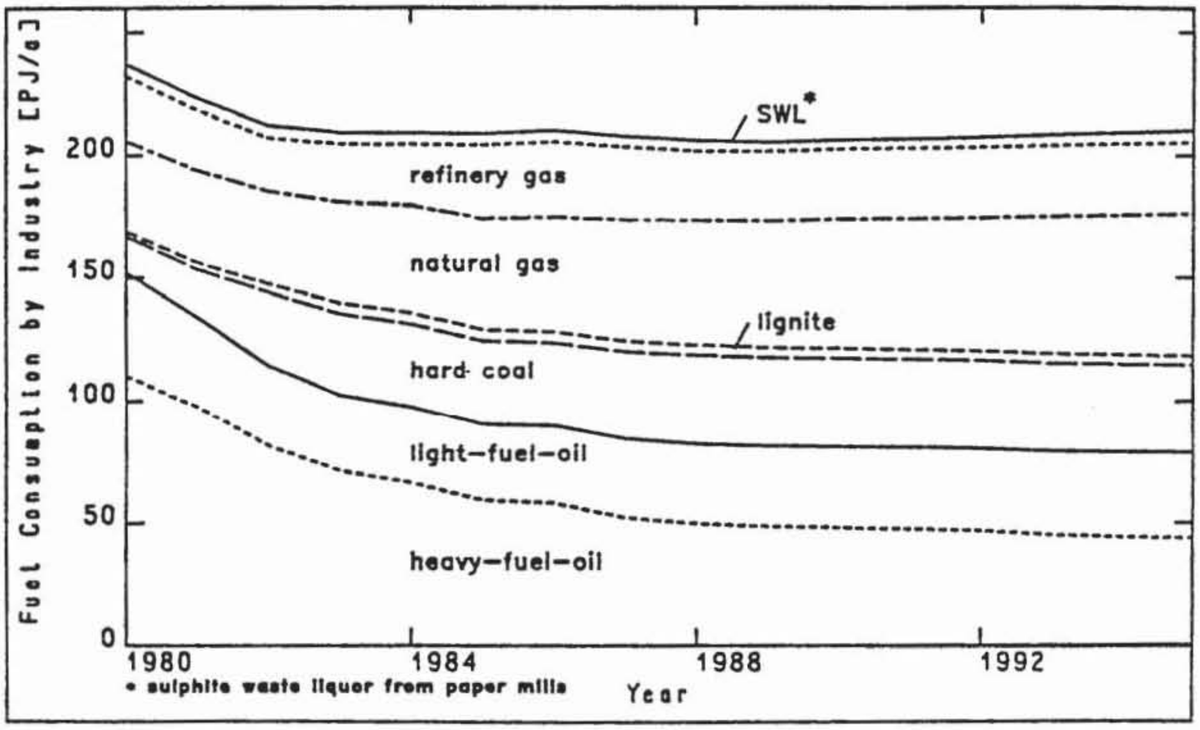
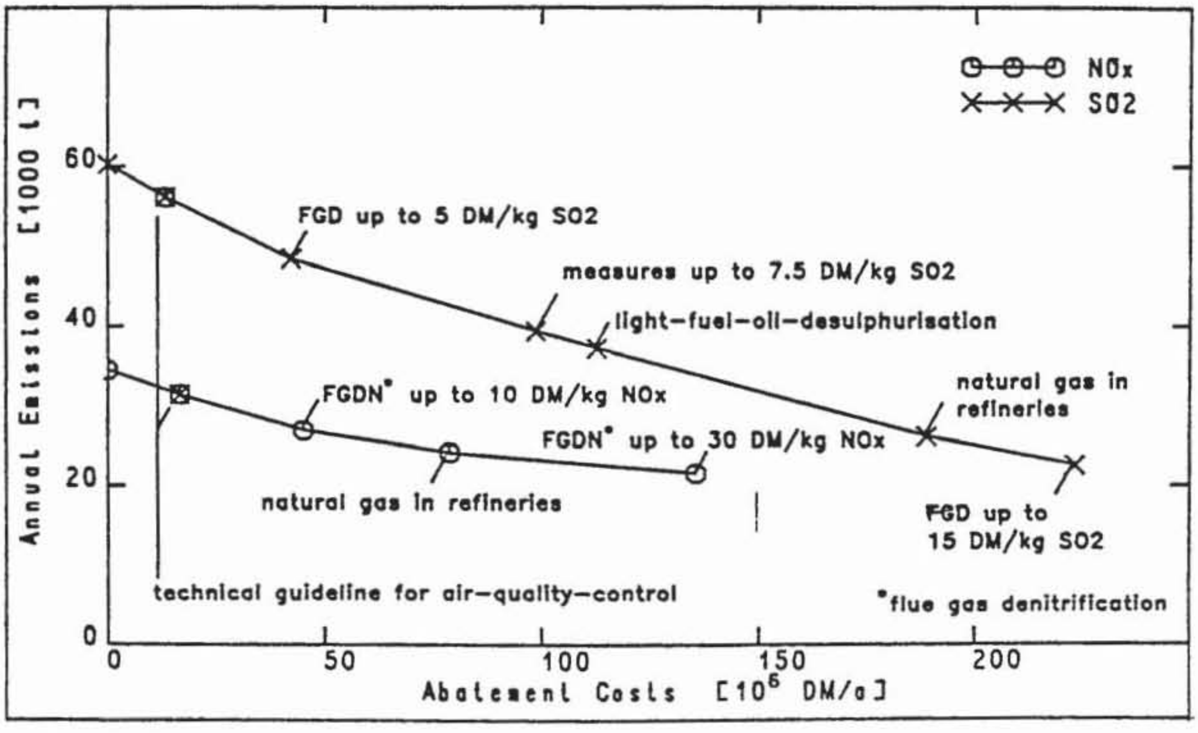



Figure 5: Cost curves for the reduction of $SO_2$- and $NO_x$-emissions in industrial firing installations



All the different emission reduction measures analysed could reduce $SO_2$-emissions from industrial firing installation from about 60 kt/a to 22.5 kt/a with associated annual costs of 220 Million DM. A reduction of $NO_x$-emissions from 34 kt/a to 21 kt/a would cost about 135 Million DM per year.

## II.C Residential and Commercial Sector

The residential and commercial sector is characterized by a large number of small size boilers used for room heating and warm water purposes. Meaningful ways of reducing $SO_2$-emissions are the substitution of coal and the use of light fuel oil with a lower sulphur content e.g. 0,15 wt %. Efficiency improvements could also contribute to emission reductions. All three of these measures could reduce $SO_2$-emissions in the mid-nineties from 23 kt/a to 8 kt/a. Coal substitution and efficiency improvements of boilers and stoves do also have a positive effect on the $NO_x$-emissions of this sector. The use of special ceramic- or steel insets in gas-stoves and combustion modification in natural gas as well as in light fuel oil boilers are meaningful ways to further reduce $NO_x$-emissions. Preliminary results achieved so far indicate that the specific reduction costs of this measures are in the range of 0 to 20 DM/kg $NO_x$. The total $NO_x$-emission reduction potential is in the order of 8 kt/a.

## II.D Transport Sector

The transport sector is the major source of $NO_x$-emissions in Baden-Württemberg. Although it is expected that until 1995 the passenger and good transport volume will increase by 6 %, related $NO_x$-emission would increase only by 1.3 % to about 233 kt. This is due to fuel efficiency improvements and an increasing share of diesel-engines, which produce only about half as much $NO_x$ as otto-type engines. These figures do not include the effect of the new emission standards set by the European Commission last year. These new emission standards for $NO_x$, HC and CO becoming effective in 1988 respectively in 1993 for new cars would reduce $NO_x$-emissions by 7 % in 1995.

The main technical means to reduce the $NO_x$-emissions of an Otto-engine are exhaust gas catalytic converters, exhaust gas recirculation (EGR) (reduction about 50 %) and the control of combustion conditions in the cylinder so that the availability of excess air is minimised. With a controlled three-way catalytic converter a 70 to 90 % emission reduction can be achieved, which drops to about 50 % if the catalytic converter is used without a lambda sampler for oxygen control. The catalytic converter technology requires the use of unleaded gasoline.

It has been mentioned already, that the new emission standards set by the Countries of the European Community will only result in a minor reduction of $NO_x$-emissions by 1995. Therefore the Federal Government has set out some fiscal and financial incentives to speed up the introduction of new low emission automobiles and to make the retrofitting of old cars attractive.

Table 2: $NO_x$-emission reduction in the transport sector

| measure | $NO_x$-emission reduction in 1995 [1000 t/a] | Reduction costs [$10^6$ DM/a] |
|---|---|---|
| retrofit of existing cars | 7.5 | 99 |
| controlled and uncontrolled three-way catalytic converter new cars | | |
| 1400-2000 ccm | 14,1 | 215 |
| >2000 ccm | 44.6 | 740 |
| total | 66.2 | 1054 |

Under the assumption that 50 % of the existing car stock will be retrofitted and that due to the incentives the share of new low emission automobiles with controlled or uncontrolled catalysts will lineary increase to 100 % until 1988 respectively 1993, the $NO_x$-emission of the transport sector could decrease from 233 kt/a to 167 kt/a in 1995, which is a reduction of about 33 %. The abatement cost would be in the order of 1000 Million DM/a (see Table 2).

## III OVERALL EMISSION CONTROL STRATEGY FOR BADEN-WÜRTTEMBERG

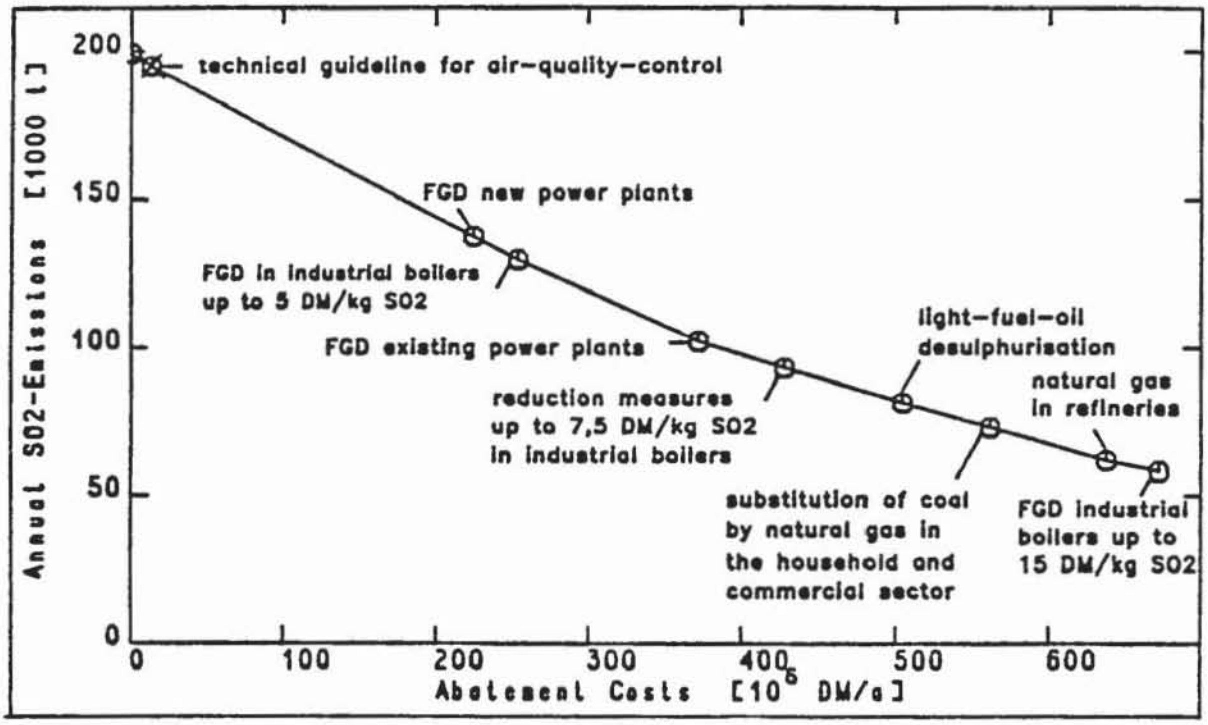
After having discussed the possibilities and costs of reducing $SO_2$- and NO -emissions in the different sectors it is now possible to design an overall control strategy taking into account all emission sources and based on the benefits of alternative control measures in relation to their costs.

Figure 6 describes the cost function of reducing $SO_2$-emissions in Baden-Württemberg, which indicates the minimal cost envelop encompassing the entire range of sulphur abatement options at the different sources for the year 1995 and a given structure of energy consumption.

$SO_2$-emissions in Baden-Württemberg could be reduced by about 70 % or 140 kt/a with an associated annual cost of about 700 Million DM. The most cost effective means in a sulphur reduction strategy are the flue gas desulphurization of large utility and industrial boilers.

To achieve similar drastic reduction of the $NO_x$-emissions in Baden-Württemberg seems to be not possible with the technologies available today. The relationship between total $NO_x$-abatement costs and the achieveable reduction of $NO_x$-emissions is given in Figure 7. With annual abatement costs of nearly 1.5 Billion DM the $NO_x$-emissions could be reduced by 37 % in the year 1995. The major contributors to the remaining emisisons are the diesel-engine automobiles and the cement industry. The most cost effective $NO_x$-reduction measure are the combustion modification techniques and the flue gas denitrification (FGDN) in large public and industrial boilers.

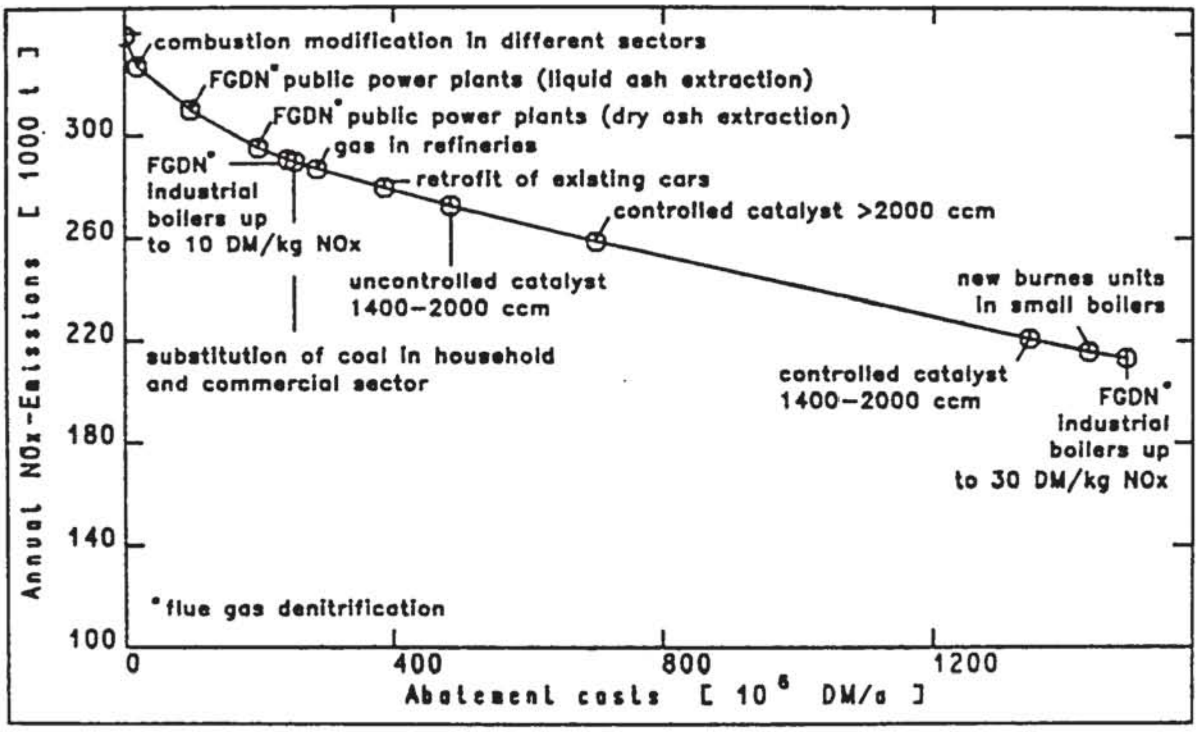
Figure 6: $SO_2$-control costs in Baden-Württemberg




The results described above, although preliminary for some sectors, show clearly that a cost-effectiveness analysis is able to provide important and useful information for the formulation of an efficient emission control strategy. Of course it cannot give answers to all important questions on the emission control issue, in particularly it cannot determine the tolerable emission levels. But it could be an essential input, based on present kowledge, to a rational and better informed decision making in an uncertain environment.

The increased attention paid to environmental problems have intensified the efforts to generate the necessary data and to develop appropriate tools - the cost-effectiveness-analysis being one ot them - for the assessment of emission control measure and for the identification of optimum control policies. Much attention has been given to the environmental implications of energy strategies. But relatively little attention has been paid so far to the questions on how alternative control policies will impact on the energy sector. The costs of control techniques, leading to higher energy prices, are in this context only one aspect which must be

Figure 7: $NO_x$-control costs in Baden-Württemberg




considered. The possible structural changes of fuel consumption in the different sectors of energy use, induced by strict emission standards or ambient air quality standards for example, seem to be another important aspect, that has not been analyzed and assessed so far.

Without trying to be exhaustive, a comprehensive analysis of the following questions is still required:

- Can energy conservation be an alternative to emission control techniques?
- How is the consumption of heavy fuel oil affected by different emission standards?
- Where will and should natural gas substitute dirty fuels for environmental reasons?
- Will nuclear electricity benefit from environmental control policies?
- Will clean energy be affordable for the economy?
- Are methanol or hydrogen the fuels of future?

Adequate answers to these questions will contribute to a balancing of energy and environmental objectives, often thought to be in conflict. They are in reality complementary objectives of society.

## REFERENCES

[1] Staatsministerium Baden-Württemberg (Hrsg.), Bericht der Arbeitsgruppe 'Energiebedarf-Umwelt-Kraftwerksbetrieb', Stuttgart 1983

[2] Staatsministerium Baden-Württemberg (Hrsg.), Minderung von Stickoxidemissionen aus Kohlekraftwerken in Baden- Württemberg, Stuttgart 1984

[3] Staatsministerium Baden-Württemberg (Hrsg.), Wirtschaftliche Entwicklung-Umwelt - Industrielle Produktion, Stuttgart 1986

[4] Voss, A., et al., Kosten-Effektivitäts-Analyse von Maßnahmen zur Reduzierung der $SO_2$- und $NO_x$-Emissionen in Ballungsräumen am Beispiel der Stadt Stuttgart, final report, KFK-PEF, in preparation

[5] Voss, A., Cost and Effectiveness of Reducing Sulphur and Nitrogen Emssions from Power Plants in Baden-Württemberg, ECE-GE.85-43208, Fourth Seminar on the Control of Sulphur and Nitrogen Oxides from Stationary Sources, Graz, Austria, 12-16 May 1986

# Annex 1

## Characterisation of Abatement Technologies

**References:**

Staatsministerium Baden-Württemberg (Hrsg.), Bericht der Arbeitsgruppe 'Energiebedarf-Umwelt-Kraftwerksbetrieb', Stuttgart 1983

Staatsministerium Baden-Württemberg (Hrsg.), Minderung von Stickoxidemissionen aus Kohlekraftwerken in Baden-Württemberg, Stuttgart 1984

Staatsministerium Baden-Württemberg (Hrsg.), Wirtschaftliche Entwicklung-Umwelt - Industrielle Produktion, Stuttgart 1986

Voss, A., et al., Kosten-Effektivitäts-Analyse von Maßnahmen zur Reduzierung der $SO_2$- und $NO_x$-Emissionen in Ballungsräumen am Beispiel der Stadt Stuttgart, final report, KFK-PEF, in preparation

| | | |
|---|---|---|
| abbreviations: | hc | hard coal |
| | hfo | heavy-fuel-oil |
| | lfo | light-fuel-oil |
| | ng | natural gas |
| | g | gasoline |

$NO_x$-Control: Combustion Modification

| control technique | fuel | control efficiency | capacity/ size | investment [DM] | O & M | emission factor after abatement measure [kg $NO_x$/TJ] | cost-effectiveness [DM/kg $NO_x$] |
|---|---|---|---|---|---|---|---|
| blue-flame burner | lfo | 50 % | - 50 kW | 350 per plant | - | 25 | 8-25 |
| packaged gas boiler unit with super stoichometric pre-mixing-burner | ng | 80 % | - 100 kW | 15 - 30 DM/kW | - | 10 | 0-15 |
| yellow flame burner | lfo | 25 % | 50-1000 kW | 500 per plant | - | 38 | 2-15 |
| atmospheric burner with radiating flame-inset of stainless steel | ng | 50 % | - 1 MW | 20-60 kW ≈ 500 DM/plant<br>> 60 kW ~ 0 | - | 30 | 0-50 |
| boiler with forced drought burner | ng | 33 % | - 1 MW | 0 | - | 40 | 0 |
| low $NO_x$-burner | lfo,hfo<br>ng | 45 % | 1 MW-200 MW | 12 DM/kW | - | hfo 140<br>lfo 77<br>ng 60 | 1-5 |
| low-$NO_x$-burner | hc | 20-30 % | > 100 MW | 0-12 DM/kW | - | 250 (dry ash extr.)<br>490 (liquid ash extr.) | 0<br>1 |

Flue-Gas-Denitrification (FGDN)

| control technique | fuel | control efficiency | capacity/ size | investment[1]) [DM/kW] | O & M[2]) | emission factor after abatement measure [mg/m³] | cost-effectiveness [DM/kg $NO_x$] |
|---|---|---|---|---|---|---|---|
| SCR | ng | 85 % | > 25 MW | 20-50 | 0,4-0,6 DM/MWh + 0,6 DM/kW·a | ≈ 100 | 3) |
| SCR | hfo | 85 % | > 25 MW | 50-120 | 0,4-0,6 DM/MWh + 2,2 DM/kW·a | ≈ 200 | 3) |
| SCR | hc | 85 % | > 25 MW | 50-180 | 0,4-2 DM/MWh + 2-10 DM/kW·a | ≈ 200 | 3) |

1) without retrofit-cost (could be 50 % and more)
2) inclusive catalyst and waste-treatment-cost
3) depends extremely on load-factor and plant size

$NO_x$-Control: Transport Sector

| control technique | fuel | control efficiency | capacity/ size | investment DM [DM/car] | O & M [DM/km] | emission factor after abatement measure [g $NO_x$/km] | cost-effectiveness [DM/kg $NO_x$] |
|---|---|---|---|---|---|---|---|
| controlled 3-way-catalyst | g | 70 - 90 % | all cars with otto-engine | 1100 | 0.0135 | 0.78 | 15-20 |
| uncontrolled catalyst | g | 50 % | all cars with otto-engine | 800 | 0.0103 | 1.3 | 10-16 |
| exhaust-gas recircula-tion (EGR) | g | 50 % | almost all cars with otto-engine | 400 | 0.0053 | 1.3 | 8-10 |
| exhaust gas recirculation with oxidizing catalyst | g | 55 % | almost all cars with otto-engine | 900 | 0.015 | 1.17 | 10-23 |

Flue-Gas-Desulphurisation (FGD)

| control technique | fuel | control efficiency | capacity/ size | investment[1] [DM/kW] | O & M[2] [DM/MWh] | emission factor after abatement measure [kg $SO_2$/TJ] | cost-effectiveness [DM/kg $SO_2$] |
|---|---|---|---|---|---|---|---|
| wet scrubber (Kroll) | lfo[4]<br>hfo[5]<br>hc[6] | 90 % | 200 kW-1 MW | 90-100 | 2-4 | lfo ≈ 13<br>hfo ≈ 85<br>hc ≈ 65 | 3-15 |
| dry-sorbent-injection | hc[6] | 60 % | > 25 MW | 30-60 | 2-3 | hc ≈ 260 | 3) |
| spray-dryer processes | hc[5]<br>hfo[6] | 90 % | > 25 MW | 70-190 | 3-6 | hc ≈ 65<br>hfo ≈ 85 | 3) |
| wet-processes | hc[5]<br>hfo[6] | 90 % | > 25 MW | 70-190 | 3-6 | hc ≈ 65<br>hfo ≈ 85 | 3) |

1) without retrofit-cost and staff (could be 50 % and more)
2) inclusive waste-treatment-cost
3) depends extremely on load-factor and plant size
4) sulphur content 0.27 wt %
5) sulphur content 1.72 wt %
6) sulphur content 0.95 wt %