Status Report

Potential and Costs for Control of NO_x Emissions in Europe

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Abstract

The various technological options for reducing emissions of NO_x from stationary sources (powerplants) and mobile sources (four-stroke gasoline engines, light and heavy-duty diesel engines) are reviewed. A framework for developing the cost estimates of these options, based upon the free exchange of control technology in Europe, is developed. Both technology-specific and country-specific parameters are used. The cost estimates for various options applied to the different stationary and mobile sources in each country can be ranked in order of cost-effectiveness to generate National Cost Curves for NO_x control in each country. These cost curves can then be used by the IIASA Regional Acidification Information and Simulation (RAINS) model to estimate the costs of various scenarios including the currently committed emission reductions and the application of best available technology. In the future, they will also be used to develop cost-optimal emission control strategies for nitrogen oxides in Europe.

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Contents

Chapter 1

Introduction

The Regional Acidification Information and Simulation (RAINS) model developed at IIASA combines information on several stages of the acidification processes in the environment: the sources of emissions and the potential for their abatement, the transport of air pollutants in the atmosphere and the environmental effects of acid deposition. These impacts are evaluated on a regional scale for the whole of Europe for forest stands, forest soils and lakes (Alcamo *et al.*, 1987). In doing so, the model includes the pathways of the main precursors of acidification SO_2, NO_x and NH_3 (Figure 1.1).

Since the RAINS model is designed as a tool for assessing the efficiency of different pollution control strategies and their environmental effects, the analysis of removal potential and control costs for different abatement strategies forms an essential part within the whole procedure. Cost functions for the control of SO_2 emissions have already been developed (Amann and Kornai, 1987). Therefore, the scope of this paper deals with the potential and the expected costs for abatement of NO_x emissions in Europe.

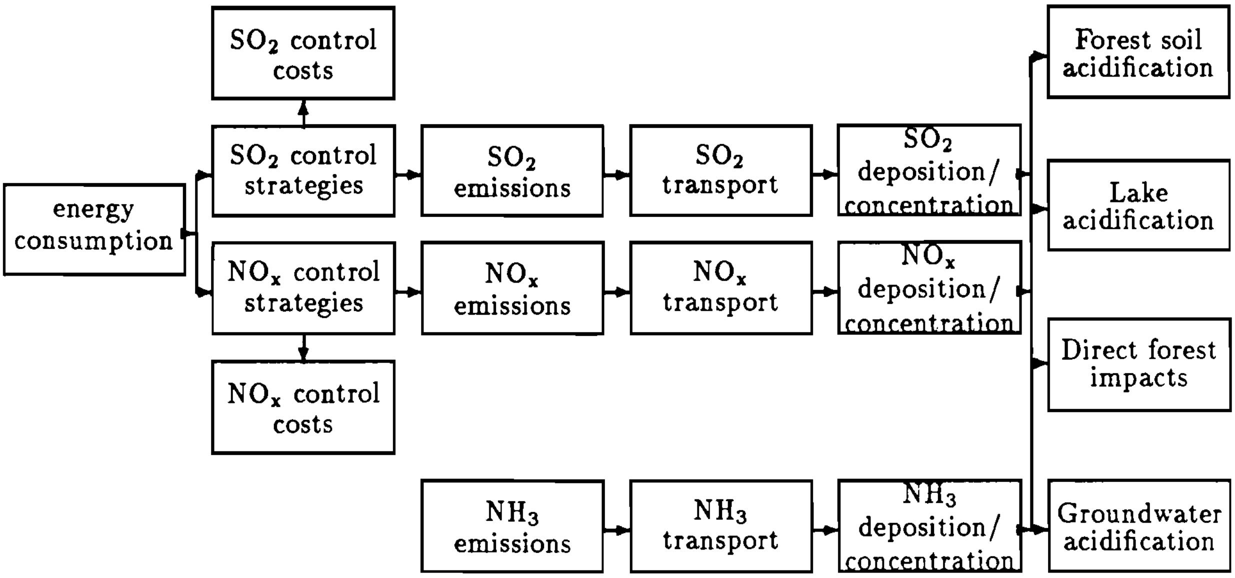

Figure 1.1: Structure of the RAINS model

Chapter 2

Emissions of nitrogen oxides

2.1 Emission mechanisms

Anthropogenic NO_x emissions originate mostly from energy combustion in stationary and mobile sources. Emissions from industrial processes (not associated with fuel combustion, e.g. the production of nitric acid) have only minor importance in Europe (Springmann, 1989). Two chemical reactions appear as the most important formation mechanisms for nitrogen oxides during the combustion of fossil fuels:

Fuel NO_x. During combustion the nitrogen chemically associated with the fuel (as apart from the molecular nitrogen which is part e.g. of natural gas) converts to amines and cyanids, which then together combine with oxygen to form nitrogen oxides. This 'fuel NO_x' formation is a function of the fuel's nitrogen content as well as of the burner type and firing mode that is used. Fuel nitrogen contents typically vary for coal between 0.5 and 2.0 percent (by weight), and are less than 1 percent for oil. In natural gas the nitrogen content is negligible (U.S. Department for Energy, 1983). Because of the simultaneous reverse reaction (i.e. formation of nitrogen from nitrogen oxides), typically only between 5 and 25 percent of the total fuel nitrogen is converted to NO_x.

Thermal NO_x. The thermal NO_x generation is due to the mechanism discovered by Zeldovich, in which nitrogen and oxygen from the air combine to form NO_x under high temperature (Equations 2.1 and 2.2).

$$N_2 + O_2 \rightarrow 2NO \tag{2.1}$$

$$N + O_2 \rightarrow NO + O \tag{2.2}$$

This formation process usually becomes important at temperatures above 1400 degrees C (Rentz, 1984), a temperature which is generally exceeded in most combustion processes. At higher temperatures, thermal NO_x generation increases exponentially. It also depends on the residence time of combustion air in the combustion chamber and the availability of excess air.

The largest fraction of nitrogen oxides emissions are emitted as NO (monoxide) and are oxidized in the atmosphere to NO_2 (dioxide). Recently greater attention has also been drawn to the generation of N_2O because of its contribution to the global greenhouse effect. For purposes of bookkeeping for emission estimates, however, all species of nitrogen oxides are usually converted to NO_2.

2.2 Emission inventories

During recent years several emission inventories have described the status of NO_x release for single European countries or for regions of Europe (e.g. Lübkert *et al.*, 1989; Pacyna, 1989; Larssen, 1989). However, up to now there has been only a limited international consistency of these estimates: Some of these efforts put emphasis on converting official national data into a common data format (e.g. the OECD-MAP emission inventory), but did not check the accuracy of the underlying emission calculations (e.g. the reasonableness of the emission factors in use). Other inventories have developed estimates based on internationally consistent sets of emission factors for some countries, but due to the limited availability of data they do not cover all of Europe.

Therefore, for the RAINS model a simplified approach was developed for calculating national NO_x emissions for all 27 European countries based on a common set of energy consumption and emission data. The energy data cover the time period from 1960 to the year 2000 with forecasts based on official data (Amann, 1989). These data are disaggregated into 6 economic sectors and 12 fuel types. In order to enable a reasonable accuracy of the NO_x emission estimates, additional breakdowns describe for each country the shares of wet bottom and dry bottom boilers in the coal powerplant sector and the fraction of two-stroke engines within the gasoline fueled car fleets.

The NO_x emission factors (describing the emission characteristics for individual combustion processes) are considered as technology-specific and are therefore assumed equal for all countries (Table 2.1). This approach enables us to reconstruct emission figures to values within reasonable ranges of those officially submitted to international organizations (Table 2.2).

Table 2.1: NO_x emissions factors (in g NO_2/GJ fuel use)

	Sector				
Fuel	Conversion	Powerplants	Domestic	Transport	Industry
Brown Coal	200	270	70	n.a.	200
Hard Coal	230	*1)*	80	n.a.	230
Derived Coal	230	n.a.	70	n.a.	230
Middle Distillates	70	n.a.	70	*2)*	70
Heavy Fuel Oil	170	200	160	n.a.	170
Gasoline	70	n.a.	n.a.	*3)*	70
Natural Gas	0	150	60	n.a.	70
Other Solids	130	n.a.	60	n.a.	130

Notes:

1)	Hard Coal, Dry bottom boiler	300
	Hard Coal, Wet bottom boiler	420
2)	Diesel, Passenger Cars and Light Duty Trucks	350
	Diesel, Heavy Duty Trucks	1300
3)	Gasoline, 4-stroke engines	750
	Gasoline, 2-stroke engines	160

Source: Springmann (1989)

Table 2.2: NO_x emissions in 1980 (in kt NO_2). Sources: Springmann (1989); UN-ECE (1988b); OECD (1989a)

Country	RAINS	ECE	OECD
Albania	28	9	-
Austria	239	216	216
Belgium	439	442	336
Bulgaria	357	150	-
CSSR	796	1204	-
Denmark	250	247	245
Finland	234	280	278
France	1944	2560	1962
FRG	2891	2950	2936
GDR	850	965	-
Greece	239	127	217
Hungary	305	270	-
Ireland	89	67	75
Italy	1458	1480	1599
Luxembourg	31	23	23
Netherlands	577	548	551
Norway	169	181	185
Poland	1597	1500	-
Portugal	149	166	165
Romania	661	390	-
Spain	950	950	937
Sweden	333	318	318
Switzerland	186	196	205
Turkey	356	175	-
UK	2324	1916	1924
USSR	9454	2790	-
Yugoslavia	394	190	-
Total	27317	20310	-

Chapter 3

Control of nitrogen oxides emissions

Emissions of nitrogen oxides can be controlled by several means:

- **Lower consumption of fuels that lead to high NO_x emissions.** The consumption of energy can be reduced (i) through a lower final demand for energy services on the consumer side, (ii) by an increased combustion efficiency and (iii) substitution of fuels that lead to high NO_x emissions by other energy forms. However, in some cases an increase in fuel efficiency may lead to higher NO_x emissions (e.g. in the transportation sector).
- The control of nitrogen oxides generation during combustion through **combustion modification** techniques;
- and the removal after combustion by **flue gas cleaning** devices.

For this study, the options for emission reductions by structural changes of the energy system were excluded. A thorough analysis of the potential for and the macroeconomic impacts of structural changes to the energy system would require detailed national models that are well beyond the present approach of the RAINS model. Such studies have already been undertaken by several researchers, but due to the complexity of the issue have focused only on a limited number of countries (e.g. Klaassen *et al.*, 1988; Rentz, 1984; Bergman *et al.*, 1988). Consequently, this study puts the emphasis on an internationally consistent assessment of direct control measures, applicable to existing energy infrastructures without major restructuring processes.

3.1 Stationary sources

3.1.1 Combustion modification

During recent years improvements in the boiler design have resulted in considerable reductions of NO_x formation during the combustion processes. Although the level of NO_x emissions from the same fuel varies considerably with the type of the plant (depending on design characteristics such as spacing of burners and fuel-to-air ratio) all combustion modification techniques make use of the same principles:

- the reduction of excess oxygen levels (especially at periods of peak temperature);
- reduction of the peak flame temperature.

There are several types of control systems, based on combustion modification, that are presently in commercial operation:

Low-NO_x burners

Low-NO_x Burners (LNB) rely on the adjustment of the flame in the combustion process to reduce both thermal and fuel NO_x formation. The advantages of LNB are ease of installation and the opportunity for retrofit in existing plants. In addition, LNB cause a minimum of energy loss from unburned particles. The reductions of NO_x emissions through use of LNB are in the range of 30 to 50 percent.

Off-stoichiometric combustion

Off-stoichiometric combustion (OSC) regulates the oxygen content in the furnace to reduce primarily the formation of fuel NO_x and secondarily the formation of some of the thermal NO_x (e.g. by 'staged combustion'). While most of the installations have been in coal-fired units, there is now also some experience with natural gas plants. The effectiveness of OSC is site- and fuel specific but generally achieves reductions up to 30 percent; for natural gas plants somewhat higher percentages seem to be feasible.

Flue gas recirculation

Flue gas recirculation has been widely used in gas- and oil-fired utilities in the United States and can result in reductions of up to 45 percent for oil plants and from 50 to 70 percent for natural gas fired facilities.

Catalytic combustion

Catalytic combustion, uses a solid surface in the combustion vessel as a catalyst. This method is presently under development and shows a potential of some 80 percent reduction of NO_x and CO and an increase in the combustion efficiency of 1 – 2 percent. However, this technology is not yet commercially available.

3.1.2 Flue gas cleaning

During recent years a variety of different flue gas treatment methods have been developed to remove NO_x after the combustion process From the large number of available processes, the 'Selective Catalytic Reduction' (SCR) has become the most important technique and is at present widely applied in some countries.

Selective catalytic reduction (SCR)

The SCR process uses ammonia to convert nitrogen oxides into molecular nitrogen (N_2) and water (H_2O) in presence of a catalyst. The most important chemical reactions are:

$$4\ NO + 4\ NH_2 + O_2 \rightarrow 2\ N_2 + 6\ H_2O \tag{3.1}$$

$$6\ NO_2 + 8\ NH_3 \rightarrow 7\ N_2 + 12\ H_2O \tag{3.2}$$

Titanium oxide TiO_2 is usually used as the catalytic material, but oxides of vanadium, molybden, tungsten, nickel and chromum are also in use. The major advantage of the SCR process is that it does not produce a by-product. The removal efficiency lies typically in the range between 80 and 90 percent and depends on the 'space velocity' (i.e. how quickly the exhaust gas stream moves through the catalysts) and on the amount of NH_3 added. After some time in operation the activity of the catalysts declines, so that they have to be exchanged periodically. However, experience shows that the originally guaranteed lifetime of some 2 years is often significantly exceeded.

The operation of the conversion process is crucially related to a certain temperature range (e.g for catalysts of titanium oxides between 300 and 400 degree Celsius). Two most common design concepts are in use:

High-dust System. The SCR reactor is situated directly after the boiler before the electrostatic precipitator and any desulfurization device.

Tail-Gas System. The catalyst is located at the end of the flue gas path after the removal of dust and sulfur. This design principle results in higher life times of the catalysts, since they are operated with almost dust-free flue gas at low concentrations of SO_2. Therefore, the plants can be designed independently of the fuel and boiler type, an advantage for retrofit applications. Any possible leaking of excess NH_3 will not have impacts on installations downstream of the SCR reactor. On the other hand, in order to maintain the necessary temperature of the conversion process, a heat exchanger and reheating have to be provided.

Operating experience with SCR is rapidly growing. Most of the existing SCR plants are in Japan, but in the FRG a major retrofitting program of SCR is also close to completion. Due to the increasing experience the prices for catalysts are declining. On the West German market for example, the price per m^3 of catalysts has shrunk from some 40.000 DM in 1985 to less than 20.000 DM today (Schärer and Haug, 1988).

Selective non-catalytic reduction

This technique controls NO_x by injection of ammonia or other reducing agents into the flue gas; the NO_x reduction takes place without use of a catalyst. The use of urea, for example, results in the following chemical reaction:

$$CO(NH_2)_2 \ + \ 2\,NO + 1/2\,O_2 \rightarrow 2\,N_2 \ + CO_2 \ + \ 2\,H_2O \qquad (3.3)$$

The SNCR process is also temperature-sensitive and, therefore, the effectiveness of NO_x removal depends on successful temperature control. In contrast to SCR technologies, no catalysts are required, which lowers the initial costs as well as the re-investment costs for catalyst replacement. Furthermore, energy costs may be lower, and less space is required. NO_x removal of about 50 percent is possible.

There are also several potential problems with the SNCR technique: The process can release ammonia; it also produces ammonium sulfate as a by-product, which can disrupt part of the system. The applicability of SCNR to coal units has not yet been demonstrated.

3.2 Mobile sources

3.2.1 NO_x control for Otto engines

The formation of NO_x in gasoline fueled Otto engines is determined by the combustion temperature, the residence time in the peak temperature zone and by the oxygen content of the fuel-to-air ratio (Figure 3.1).

Nowadays gasoline engines without emission controls are usually operated with stoichiometric or slightly over-stoichiometric fuel-to-air ratio, whereas engines built in the sixties were designed to operate below stoichiometricy. The resulting high CO emissions of the early designs initiated the first technical regulations to limit CO emissions. The new engines indeed reduced the CO and VOC emissions, but at the same time (due to the higher stoichiometric ratio) the NO_x emissions increased drastically.

There are several means of reducing NO_x emissions from gasoline fueled cars:

Exhaust gas recirculation (EGR)

The recirculation of exhaust gases substitutes part of the fresh intake air by exhaust gas, reducing the oxygen content in the combustion chamber and dampening the temperature peaks through its additional heat capacity. Both effects contribute to lower NO_x emissions. Removal efficiencies of up to 30 percent are achievable without any increase in fuel consumption.

Lean burn engines

A change in the stoichiometricy of the fuel-to-air ratio towards leaner mixtures also results in reduced NO_x emissions. To guarantee satisfactory operation of the engines, some changes in the general design of the engines are necessary. Therefore, only new engines can be designed along the lean burn concept. The cars presently available with lean burn engines show satisfac-

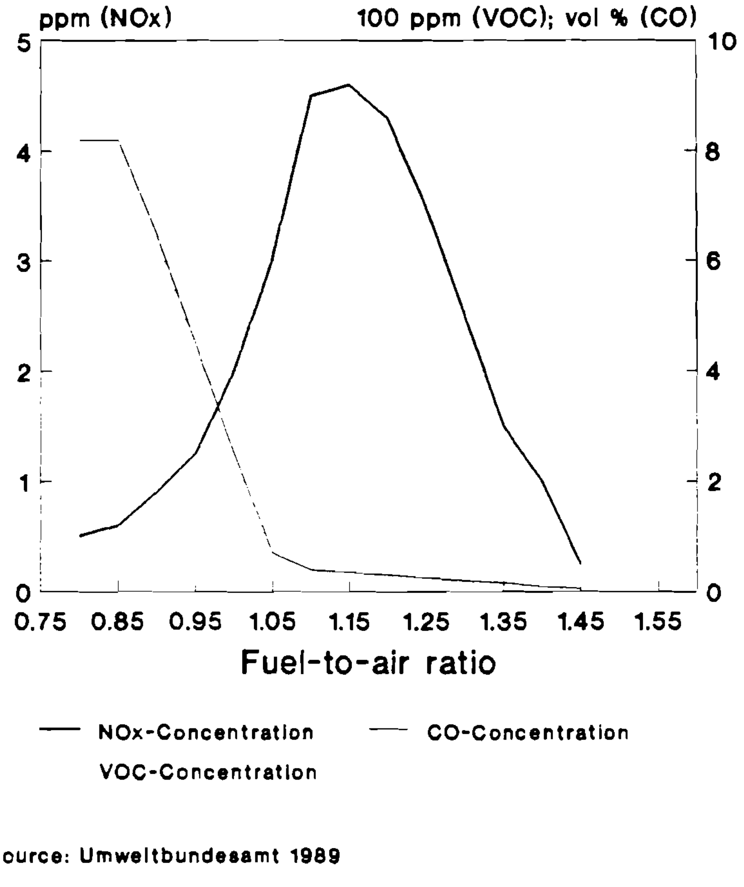

Figure 3.1: Variation of emission levels with fuel-to-air ratio λ for an Otto-Cycle Engine

tory NO_x reduction for lower speed and comply with the ECE standards; at high speed, however, due to the high oxygen content of the exhaust gas their emissions may exceed those of conventional cars without control.

Catalytic reduction

A catalytic converter enables and accelerates the chemical conversion of CO, VOCs and NO_x to CO_2, H_2O and N_2 at temperatures well below that at which it would occur spontaneously. The oxidation of CO and VOC is facilitated by completing the combustion process, nitrogen oxides are catalytically reduced. The catalysts consist of ceramic materials coated with precious metals (platinum, palladium or rhodium) or with active metal oxides (e.g. gamma alumina, copper oxide, etc.). Catalysts require the use of lead-free fuels, since the leaded antiknock additives form inorganic lead salts deposit on the catalytic surface, thereby deactivating it.

The **three-way catalytic** concept uses a single unit which oxidizes CO and VOC to carbon dioxide and reduces NO_x to nitrogen. For this process to work, it is necessary to have very careful control of the concentrations of all the gases on the catalytic surface. Therefore, these systems require a fuel injection system capable of maintaining precise control of the fuel-to-air ratios under all driving conditions. This is usually achieved by means of electronic fuel injection on 'feedback' carburettors combined with an oxygen sensor in the exhaust gas stream. The catalytic unit is programmed to control some 70 to 90 percent of the CO/VOC/NO_x during urban driving and up to 99 percent at high speed.

The **uncontrolled catalyst** does not control the fuel-to-air ratio and therefore does not require the fuel injection system and the oxygen sensor. Consequently, the catalyst works partly in the oxidizing mode (mainly reducing CO and VOCs) and partly in a NO_x reducing mode (lowering

NO_x). The resulting NO_x removal is lower than with controlled three way catalysts, but for smaller sized cars meets the requirements of the 'Luxembourg compromise' of the European Community.

There are also other catalytic systems available (e.g. the oxidation catalyst), but they do not have impacts on NO_x emissions.

Two-stroke engines

There are a large number of two-stroke operated vehicles in some Eastern European countries. These conventional engines produce a comparably large amount of CO and VOC emissions, but only low emissions of NO_x. Since the production of these engines in Europe has been virtually stopped this year, no control options are considered. However, a 'stratified charge two-stroke' concept would enable drastic reduction of all three pollutants with CO and NO_x rates below those of comparable four-stroke engines.

3.2.2 Diesel engines

The high pressures and temperatures, and the relatively low fuel-to-air ratios in diesel engines reduce the incomplete combustion, making these engines more fuel efficient than spark-ignition engines. Due to the lower degree of incomplete combustion, diesel engines emit lower amounts of HC and CO than do Otto engines, whereas NO_x emissions are the same or lower. Approximately 10 to 20 percent of nitrogen oxides from diesel engines are emitted as NO_2 (nitrogen dioxide), which is five times more toxic than NO (nitrogen monoxide). Gasoline engines emit less than 10 percent as NO_2. However, in the atmosphere this NO converts to NO_2 within a short time.

For diesel engines there is also an inherent conflict between some of the most powerful NO_x control techniques and the emissions of particulates. This 'tradeoff' is not absolute – various NO_x control techniques have varying effects on soot and VOC emissions, and the importance of these effects varies with engine speed and load. These tradeoffs place limits on the extent to which any one of the three pollutants can be reduced. At the moment there is no aftertreatment technique commercially available to reduce NO_x emissions from diesel engines. The process of catalytic NO_x reduction used on gasoline vehicles is inapplicable to diesel; because of their heterogeneous combustion process, diesel engines require substantial excess air, and their exhaust thus inherently contains significant oxygen. The three-way catalyst used on automobiles requires a precise stoichiometric mixture in the exhaust to properly function; in the presence of excess oxygen, their NO_x conversion efficiency rapidly approaches zero.

A number of aftertreatment NO_x reduction techniques which *will* work in an oxidizing exhaust stream are currently available or under development for stationary sources (e.g. Selective Catalytic Reduction SCR, Selective Non-Catalytic Reduction SNCR, etc.). However, each of these systems require a continuous supply of some reducing agent such as ammonia. Because of the need for frequent replenishment of this agent and the questions of crash safety, such systems are considered impractical for vehicular use.

Diesel passenger cars

Usually the design of the engines of diesel passenger cars use the indirect injection concept, in contrast to engines for heavy duty trucks, which are built as direct injection engines. The direct injection results typically in twice as high NO_x emissions as the indirect injection design.

In a manner analogous to that for gasoline engines, combustion modifications (exhaust gas recirculation (EGR), delayed injection and staged combustion) can be used for the reduction of NO_x emissions. EGR reduces the partial pressure for oxygen and the combustion temperature, leading to reduced NO_x formation. Although for partial load emission reduction of some 20 to 30 percent is achievable, the strong increase of particulate matter generation limits the recirculation of the exhaust gases at full load.

Heavy Duty Trucks

There is no single technology for drastically reducing NO_x emissions from heavy duty trucks without major adverse impacts on the emissions of soot, VOC and noise, and on the fuel efficiency. However, some emission reductions can be achieved by the following measures:

Injection Timing. The timing relationship between the beginning of the fuel injection and the top of the compression stroke of the piston has an important effect on diesel engine emissions and fuel economy. For purposes of fuel efficiency it is preferable that the combustion begins just at the point of greatest compression, which requires fuel injection somewhat before this point. A long ignition delay provides more time for air and fuel to mix, which increases both the amount of fuel that burns in the premixed combustion phase and the maximum temperature in the cylinder. Both of these effects tend to increase NO_x emissions, but reduce particulate and VOC emissions. Therefore, the injection timing must compromise between emissions of particulates and VOC and fuel economy on one hand and noise, NO_x emissions and maximum cylinder pressure on the other. A higher injection pressure might eleviate the need for this compromise.

Turbocharging and Intercooling. A turbocharger consists of a centrifugal air compressor feeding the intake manifold, mounted on the same shaft as an exhaust gas turbine in the exhaust stream. By increasing the mass of air in the cylinder prior to compression, turbocharging correspondingly increases the amount of fuel that can be burned without excessive smoke, the potential maximum power output and the the fuel efficiency of the engine. The compressed air can be cooled in an intercooler before it enters the cylinder. This increase of the air mass in the cylinder and the reduction of its temperature can reduce both NO_x and particulate emissions. In the U.S., virtually all engines will be equipped with these systems by 1991.

Exhaust Gas Recirculation. EGR is a time-proven NO_x control technique for light-duty gasoline and diesel vehicles. In heavy-duty trucks, EGR has been shown to increase wear rates and oil contamination, resulting in higher maintenance expenses and shorter engine life (Cadman and Johnson, 1986). It is also considered to have little advantage over other NO_x control techniques such as retarding injection time. However, some recent research results suggest that a re-evaluation of this technique may be in order.

3.3 NO_x control options selected for cost evaluation

Since the RAINS model can only deal with a limited number of control options for each combustion sector, the most important NO_x reduction techniques were identified and costs evaluated. Within the model each control option is basically described by its abatement costs and removal efficiency. Thus these economic properties of the most common NO_x abatement options also represent other techniques with the same cost-efficiency ratio, especially since these alternative methods have to compete on the market against the predominant techniques.

3.3.1 Stationary sources

For stationary sources (powerplants, industry) two groups of NO_x control options were selected:

Combustion Modifications. This group describes the control of NO_x emissions by optimizing boiler design, applying 'Low-NO_x burners' and 'Off-stoichiometric combustion'. These options are available both for the construction of new plants and for retrofit application to existing units. An average NO_x removal efficiency of 30 percent is assumed to be achievable with these processes without impacts on CO and VOC emissions. Since the underlying design principles are already part of the general technical standards, it seems reasonable to assume that the planning of all new plants will automatically incorporate these construction guidelines. Advanced methods, such as catalytic combustion, are not considered in this analysis due to the lack of operating experience. If such a technology becomes available and proves to be commercially successful, the overall technical and economic performance would have to be equal or even better than those of conventional methods. For this reason, the procedure that we have selected has a tendency to overestimate future control costs.

Flue Gas Cleaning. The most common flue gas cleaning technique in Europe at present is Selective Catalytic Reduction (SCR) with an assumed average NO_x reduction of some 80 percent, in compliance with the U.S. standard of 1985. In theory there might be better control technologies than SCR, but, due to its dominating market position and the large construction and operating experience gained in Europe, it will be difficult for other methods to compete with the SCR process.

Combined NO_x Control. Because these two control options apply to different parts of the NO_x formation process, it is also possible to combine primary measures such as combustion modification and secondary options such as SCR. The resulting removal efficiency (compared to uncontrolled combustion) could reach 90 percent. Because of the lower NO_x concentration at the inlet of the SCR plant the consumption of reaction agents (NH_3) will be reduced, resulting in lower operating expenditures for the SCR unit.

3.3.2 Mobile sources

The data base for mobile sources comprises four categories:

- Gasoline fueled cars with four-stroke Otto engines
- Gasoline fueled cars with two-stroke Otto engines
- Diesel fueled passenger cars and light-duty trucks
- Diesel fueled heavy duty trucks

For gasoline fueled cars with **four-stroke engines** two levels of NO_x control are considered:

- A moderate reduction, describing technical solutions to fullfil existing regulations such as the **EEC-Luxembourg compromise** for smaller cars. This involves several kinds of engine modifications (including EGR and the concept of the Lean Burn Engines) as well as the application of uncontrolled catalytic converters. The NO_x reduction efficiency (compared to uncontrolled engines) lies typically around 50 percent. Due to the lack of sufficient operating experience in lean burn engines, the cost estimates for this degree of control is based on the costs of the uncontrolled catalyst. It is assumed that the emissions of CO and VOCs are also simultaneously reduced by 50 percent.
- More complex control concepts to comply with the **U.S. 1985 Standards**. These standards, which require an average reduction of at least 80 percent compared to the uncontrolled case, can currently be met by application of the three-way catalyst. Some countries have already adopted these regulations: USA, Canada, Japan, Austria, Finland, Norway, Switzerland and Sweden for the whole fleet and the EEC

countries for cars with cylinder volumes of more than 2 litres. Emissions of CO and VOC are simultaneously reduced to the same degree.

As mentioned above, because of the low importance of **two-stroke engines** in Western Europe and the low probability of retrofits for existing Eastern European cars, no NO_x control is considered for this group of vehicles.

For **diesel passenger cars a group** of engine modifications is included to reduce their emissions by 30 percent. These reductions can be achieved by EGR, delayed injection and staged combustion.

Because of the importance of **Heavy Duty Trucks** for European NO_x emissions, two levels of NO_x control are specified. The uncontrolled status is based on the ECE guideline ECE.R49, which is comparable to pre-1988 U.S. Federal emission standards. This regulation represents a lowest common level of diesel engine technology worldwide, including a small retardation of the injection timing in order to reduce NO_x, use of special injection nozzles to reduce HC and particulate matter, and some smoke control measures.

U.S. 1988 Standards This level of control is intended to reflect current (1988-1990) diesel engine technology in the U.S. While this level of technology is now required in the U.S., it is not unique to the U.S. and is already often applied in modern European trucks. The emissions of NO_x are reduced by 25 percent (compared to the base case of the ECE.R49 regulation) with no impacts on VOCs, particulate matter and CO. The standards can be met via turbocharging with air-to-air or low-temperature air-water aftercooling. Further NO_x control is provided by moderately retarded fuel injection at increased injection pressure. For the most part, this involves only incremental changes to the existing technology, rather than major redesign.

U.S. 1991 Standards This level of emission control reflects essentially the coming state-of-the-art in diesel engine technologies – those being developed in compliance with the U.S. 1991 emission standards. These standards represent roughly the feasibility for in-cylinder emission control alone (using currently available technology). The effect on NO_x emissions is a 40 percent reduction, and can be achieved only by a complete redesign of large portions of the engine and combustion system. Besides the complete change of the in-chamber combustion conditions, NO_x reductions are maximized through electronically controlled retardation of the fuel injection over most of the speed/load range and cooling the compressed air as much as possible. Through complex design guidelines, a simultaneous reduction by 50 percent for VOC and PM emissions can be achieved.

Chapter 4

Costs of NO_X abatement

4.1 Principles of cost calculation

The intention of the approach in this report is to identify the values to society of the resources diverted in order to reduce NO_x emissions in Europe. In practice, these values are approximated by estimating costs at the production level, rather than prices to the consumers. Therefore, any mark-ups charged over production costs by manufacturers or dealers do not represent actual resource use and are ignored. Certainly there will be transfers of money that have impacts on the distribution of income or on the competitiveness of the market, but these should be removed when considering the efficiency of resource allocation (see e.g. Transport Canada, 1986). Any taxes added to the production costs are similarly ignored as transfers.

The analysis will produce a framework to estimate these values in a consistent way for all European countries despite the differences between their economic systems. To eliminate the influence of these economic differences, a basic assumption was made of the existence of a free exchange of control technologies in Europe. Furthermore, it was assumed that on the competitive market technologies will be available for all countries at equal costs.

The results of the economic evaluation of NO_x control options will not predict costs for specific plants in individual countries, but will enable a general comparative analysis of different pollution control options for different countries, source categories and fuel types. The main objective of the approach, however, is the consistent international comparison of

- costs for different NO_x abatement strategies, based on different energy scenarios; and
- a comparison of pollution control costs among countries.

The necessity to assess abatement costs for all countries in Europe limits the level of detail which can be maintained. Data availability and computational constraints require simplifications which might appear too approximate for studies focused on one country only. Therefore, the results of the economic evaluation should be considered more as indicative than as absolute cost estimates: the main emphasis is put on international consistency and comparability.

4.1.1 International consistency

There are not only economic but also structural differences in national energy infrastructures, resulting in variations of the actual costs of the application of a given set of technologies. For example, the same type of an SCR unit with the same investment costs will reduce more NO_x if installed in a powerplant running in a baseload mode than in a peak load mode. Consequently, the costs per abated ton of NO_x will be greater in the latter case. In reality, the average capacity utilization as well as the boiler size distribution has a significant influence on the abatement costs in a country.

The second major influence on costs of national abatement strategies is the structure of energy consumption. Different source categories require different control efforts and costs. Not surprisingly, the costs necessary to achieve certain levels of emission reductions are directly related to the actual potential for applying control options to certain source categories. Therefore, the characteristics of national energy systems (importance of coal use, share of the transport sector, etc.) produces major differences in potential and costs for emission reductions.

4.1.2 Benefits of NO_x control

The final goal of each NO_x control measure is the reduction of the adverse effects to human health, natural resources and manmade material of nitrogen deposition or concentration in the atmosphere. It is a major objective of the RAINS model to quantify such negative effects. However, at the moment the model does not express any benefits achieved by emission reductions in monetary terms, but restricts itself to the prediction of observable physical variables (such as pH values, areas of forest at risk, etc.). Therefore, the economic evaluation of NO_x control excludes such benefits of emission reductions and concentrates purely on the abatement costs (resources) necessary to achieve the abatement.

Similarly also macroeconomic effects and potential benefits (e.g. impacts on the employment rate, trade balance, energy prices, crowding out of capital, etc.) are also excluded from this first analysis.

A difficult problem arises when control technologies for NO_x simultaneously reduce (or possibly increase) the emissions of other air pollutants (e.g. the three-way catalytic converter also reduces CO and VOC). The overall economic evaluation of such techniques depends crucially on the value attributed to the emission reductions of these pollutants. If the control of NO_x is selected as a single target, such control options may turn out as less cost efficient than other techniques (e.g. reducing just NO_x at lower costs). On the other hand, if they are evaluated in an integrated context, where the reduction of other substances is also of interest, they may turn out to be extremely cost-efficient compared to a set of other measures necessary to achieve the same improvements.

However, even if it would be the consensus that future policies have to consider several pollutants, the question of the relative importance of emission reductions for individual substances would still remain open. In principle, such tools as the RAINS model can be used to analyse the tradeoffs between different pollutants for specific problems (such as the acidification process in the environment) and thereby derive the relative importance of pollutants. However, in reality the problems are multi-facetted and, therefore, no simple solution seems available within the near future. This means that, for this analysis, the weighting of achieved emission reductions for different emission reductions remains open to subjective judgement.

4.2 Economic method

The method of cost estimation applied in this study uses standard methods of investment analysis applied to the question of emission abatement from a public policy perspective (Rentz, 1987). As explained above, a business perspective would very likely use these techniques in a slightly different way because of financial and profit considerations, which are not appropriate for public policy. Specifically, this difference of perspective would affect such parameters as discount rate, plant lifetime, financial outlays versus real resource costs, etc.

The objective of the abatment investment analysis is to calculate the *life cycle costs* of reducing emissions from individual source types and to relate these costs to the emission abatement achieved. Because costs are incurred, and revenues or benefits (e.g. abatement) are received at different points in time, it is necessary to choose one point in time for aggregation and comparison. A *present value* (PV) is the value that the flow of all costs or all benefits would have if they were accrued to today, or to a year zero. A *levelized* cost or emission reduction is the annual value that would have to be paid or received each year over the lifetime of the abatement system to be equivalent to a given PV; that is, if the PV were evenly spread over the lifetime of the system.

To approximate the values of future costs or benefits to a present value the method of ***discounting*** is generally used. Interest rates are one form of discount rates determined by supply and demand (alternative uses) of money. So are ***opportunity costs***. The appropriate discount rate to use for public policy analysis is very controversial and must consider several points:

- the cost of borrowing money;
- the 'opportunity costs' or the return that would be feasible by putting those resources to some other use, including returns that may not be valued by private markets (i.e. social benefits);
- subjective rate of time preference;
- consideration of future generations of people and resource bases.

For this analysis the use of a real discount rate (nominal discount rate – inflation rate) eliminates the difficulty of projecting future inflation.

4.3 Stationary sources

4.3.1 The algorithm for the cost evaluation

In order to calculate the life-cycle costs according to the investment analysis method it is necessary to differentiate the expenditures into

- investment costs,
- cost items depending on investments, and
- operating costs.

Investment costs

The investment costs include the expenditure accumulated until the start-up of an installation, such as delivery of the installation, construction, civil works, ducting, engineering and consulting, licence fees, land requirement, working capital (e.g. stocks, process delays) etc. The model does not account for these cost items individually, but allows the use of aggregated investment functions.

The following description uses the indices i, j, k and l to indicate the nature of the parameters:

i	denotes the fuel type
j	the economic sector
k	the control technology
l	the country.

If there is a size dependency of the unit investment costs $I_{i,j,k,l}$ (e.g. due to 'economics of scale'), it can be incorporated into the model by equation 4.1. The necessary size of an abatement installation for a certain plant capacity bs_i is determined by the fuel-specific flue gas volume v_i to be handled. The form of the function is described by its coefficients ci^f and ci^v. The more complicated situations arising for retrofit applications are taken into account by a retrofit cost factor r_k. Since the investment cost functions are usually scaled to output capacities of plants (e.g. MW_{el}), the thermal efficiency of the combustion process $eff_{i,j,l}$ is used to relate the costs to fuel input.

$$I_{i,j,k,l} = (ci_k^f + \frac{ci_k^v}{bs_{i,j,l}})\, v_i \,/\, r_k \;\, eff_{i,j,l} \tag{4.1}$$

The investment cost functions decribe only the costs for construction of the equipment, and exclude the costs for the catalytic material. Since these costs depend on the actual operation of the plant, they will be accounted for under the cost item 'variable operating costs'.

The investments are annualized over the plant lifetime $lt_{j,k}$, using the interest rate q_l (equation 4.2).

$$I^{an}_{i,j,k,l} = I_{i,j,k,l} \frac{{q_l}^{lt_{j,k}} (q_l - 1)}{{q_l}^{lt_{j,k}} - 1} \tag{4.2}$$

Investment related costs

The annual fixed expenditures OM^{fix} cover the costs of maintenance, taxes and administrative overhead. These cost items are not related to the actual use of the plant. In contrast to desulfurization plants, no additional labor requirements are reported for NO_x control equipment, because the operation of the devices is automatically controlled to a high degree. As a rough estimate for the annual fixed expenditures, most technical standards use a standard percentage f_k of the total investments costs:

$$OM^{fix}_{i,j,k,l} = I_{i,j,k,l}\, f_k \tag{4.3}$$

Operating costs

The variable operating costs OM^{var} related to the actual operation of the plant take into account the costs for the increased energy demand for operating the device (e.g. for the fans and for reheating) and for sorbent material (e.g. NH_3.). These cost items are calculated based on the specific demand λ^x of a certain control technology and its (country-specific) price c^x.

$$OM^{var}_{i,j,k,l} = \lambda^e_k\, c^e_l + nox_{i,j,k}\, x_{i,j,k}\, \lambda^s_k\, c^s_l \tag{4.4}$$

λ^e	additional energy demand
λ^s	sorbents demand
c^s	sorbents price
c^e	energy price
$nox_{i,j,k}$	NO_x emission factor
$x_{i,j,k}$	removal efficiency

If a control technology makes use of catalysts, the periodical replacement costs for this equipment (depending on the real operation time of the plant) is also included in this cost category:

$$OM^{cat}_{i,j,k,l} = \lambda^{cat}_{i,j}\; v_i\; eff_{i,j}\; ci^{cat}\; pf_{i,j,l} \;/\; lt^{cat}_k \tag{4.5}$$

λ^{cat}	catalyst volume
ci^{cat}	costs of catalysts
$pf_{i,j,l}$	operating time
lt^{cat}	lifetime of catalysts.

Unit costs of NO_x control

Based on the above mentioned cost items, the unit costs for the removal of NO_x emissions can be calculated. In Equation 4.6 all expenditures of a control technology are related to one unit of fuel input $ce_{i,j,k,l}$. The investment related costs are converted to fuel input by appplying the capacity utilization factor $pf_{i,j,l}$:

$$ce_{i,j,k,l} = \frac{I^{an}_{i,j,k,l} + OM^{fix}_{i,j,k,l}}{pf_{i,j,l}} + OM^{var}_{i,j,k,l} + OM^{cat}_{i,j,k,l} \tag{4.6}$$

Although this cost coefficient $ce_{i,j,k,l}$ is useful for the calculation of price effects on the electricity price, the cost efficiency of different control options can only be evaluated by relating the abatement costs to the amount of reduced NO_x emissions. However, at this point, the question, of how simultaneous reductions of emissions other than NO_x should be credited becomes crucial. As can be seen in Equation 4.8, the overall figure of cost efficieny $cn'_{i,j,k,l}$ is extremely sensitive to the relative weight factors f^{NOx}, f^{CO} and f^{VOC}:

$$cn_{i,j,k,l} = \frac{ce_{i,j,k,l}}{nox_{i,j}\, x_k} \tag{4.7}$$

$$cn'_{i,j,k,l} = \frac{ce_{i,j,k,l}}{nox_{i,j}\, x_k^{NOx}\, f^{NOx} + voc_{i,j}\, x_k^{VOC}\, f^{VOC} + co_{i,j}\, x_k^{CO}\, f^{CO}} \tag{4.8}$$

4.3.2 Data for cost calculation

Types of data

The RAINS model uses two groups of parameters for the above cost calculation routine:

- **Technology-specific** data describe the typical economic and technical properties of control technologies and are assumed to be equal for all countries under consideration. This group comprises the *technical* parameters (removal efficiency, technical lifetime, requirements for energy and sorbents material, and the *economic* parameters of the investment cost functions, the costs of catalysts, additional expenditures for retrofit installations and maintenance costs.

- **Country-specific** data describe the specific conditions in individual countries under which abatement technologies have to be applied. The most important parameters are the average capacity utilization of plants, the average boiler size, interest rates and the prices for energy and material consumption (see Table 4.1).

Table 4.1: Parameters used in the cost calculation routine

Technology-specific parameters	
ci^f, ci^v	parameters for investment cost function
ci^{cat}	costs of catalysts
f_k	annual maintenance costs
$lt_{j,k}$	lifetime of installation
lt_k^{cat}	lifetime of catalyst
x_k	NO_x removal efficiency
λ_k^e	additional energy demand
λ_k^s	material consumption
Country-specific parameters	
$pf_{i,j,k}$	capacity utilization
$bs_{i,j,k}$	average boiler size
q_l	interest rate
c_l^e	energy(electricity) price
c_l^s	price for sorbents (e.g. NH_3)

Data sources

Since there is already a large amount of experience in NO_x control in some European countries, the RAINS model uses primarily European data and, to a lesser extent, North American and Japanese sources. Recently data have become available which are based on surveys of real expenditures (Jung, 1988; Schärer and Haug, 1987; OECD, 1988; Leggett and Corfee, 1987). A comparison of data from FRG, e.g. with that from the Netherlands shows good agreement for all major control technologies (Schärer and Haug, 1988; Okken 1988). They are assumed to be fairly representative for all of Europe and were therefore adopted in the RAINS model.

The country-specific data were compiled by IIASA and are based – as far as possible – on international statistics: Average boiler sizes and national capacity utilization is based on OECD/IEA statistics (e.g. OECD, 1989b). The costs of the increased energy consumption caused by flue gas cleaning devices are based on national electricity prices for industrial consumers (losses of income if electricity cannot be sold). For IEA countries, statistical material is available from IEA (OECD, 1989c). Due to the lack of a valid conversion rate for non-convertible currencies for Eastern European countries the revenues for electricity exports to Western countries are taken as opportunity costs for increased losses during power generation. Although the model provides the possibility of applying country-specific interest rates, for reasons of international consistency and equity a flat rate of 4 percent is used for all of Europe. In the same way, the world market price for ammonia is used as input price for all national economies. Tables 4.2 to 4.5 give an overview on the data used for the calculations:

Table 4.2: Technology-specific data for stationary sources

Parameter		CM	SCR	CM + SCR	Units
NO_x removal efficiency	x_k	50	80	90	%
VOC removal efficiency	x'_k	0	0	0	%
CO removal efficiency	x''_k	0	0	0	%
lifetime in powerplants	lt_j, k	30	30	30	years
lifetime in industry	lt_j, k	20	20	20	years
coefficients for the	ci^f_k	20	41	61	
investment function	ci^v_k	5834	5834	5834	
cost of catalysts	ci^{cat}_k	–	40000	40000	DM/m^3
lifetime of catalyst	lt^{cat}_k	–	12000	12000	hours
annual maintenance and overhead	f_k	0	6	6	% of total investments
NH_3 consumption	λ^s_k	0	250.	111.	kg / t NO_x
additional energy consumption	λ^e_k	0	2	2	%

CM	Combustion Modification
SCR	Selective Catalytic Reduction

Table 4.3: Capacity utilization for powerplants (in hours per year)

Country	*Brown Coal*	*Hard Coal*	*Heavy Fuel Oil, Natural Gas*
Albania	4000	4000	4000
Austria	3504	3504	3066
Belgium	n.a.	3416	3679
Bulgaria	4818	4818	4380
CSSR	4818	4818	3153
Denmark	n.a.	3592	526
Finland	n.a.	2365	3854
France	3767	3767	1489
FRG	6745	4205	1226
GDR	4818	4818	2716
Greece	6132	4000	3504
Hungary	4292	4292	4292
Ireland	n.a.	3592	3416
Italy	3679	4030	4030
Luxembourg	n.a.	3504	3504
Netherlands	n.a.	3154	3942
Norway	n.a.	n.a.	964
Poland	4380	4468	4468
Portugal	4000	4117	4117
Romania	4380	4380	4380
Spain	4730	4468	4468
Sweden	n.a.	4000	1314
Switzerland	n.a.	n.a.	1401
Turkey	4993	2978	2978
UK	n.a.	4468	876
USSR	5168	5168	5168
Yugoslavia	4380	1927	1927

Table 4.4: Average boiler size for powerplants (in MW_{el})

Country	*Brown Coal*	*Hard Coal*	*Heavy Fuel Oil, Natural Gas*
Albania	210	210	210
Austria	139	220	128
Belgium	n.a.	160	158
Bulgaria	210	210	210
CSSR	210	210	210
Denmark	n.a.	178	201
Finland	n.a.	134	82
France	202	252	306
FRG	235	206	190
GDR	210	210	210
Greece	243	210	155
Hungary	210	210	210
Ireland	n.a.	300	106
Italy	153	335	227
Luxembourg	n.a.	210	210
Netherlands	n.a.	328	193
Norway	n.a.	n.a.	210
Poland	210	210	210
Portugal	210	300	150
Romania	210	210	210
Spain	257	254	195
Sweden	n.a.	502	203
Switzerland	n.a.	210	150
Turkey	195	150	126
UK	n.a.	245	291
USSR	210	210	210
Yugoslavia	99	370	149

Table 4.5: Electricity price, real interest rate and NH_3 prices in Europe

Country	*Electricity Price DM/MWh*	*Interest Rate %*	NH_3 *Costs DM/t* NH_3
Albania	88	4.0	700
Austria	125	4.0	700
Belgium	97	4.0	700
Bulgaria	88	4.0	700
CSSR	88	4.0	700
Denmark	102	4.0	700
Finland	95	4.0	700
France	82	4.0	700
FRG	147	4.0	700
GDR	88	4.0	700
Greece	125	4.0	700
Hungary	88	4.0	700
Ireland	145	4.0	700
Italy	124	4.0	700
Luxembourg	114	4.0	700
Netherlands	86	4.0	700
Norway	31	4.0	700
Poland	88	4.0	700
Portugal	162	4.0	700
Romania	88	4.0	700
Spain	108	4.0	700
Sweden	88	4.0	700
Switzerland	142	4.0	700
Turkey	87	4.0	700
UK	126	4.0	700
USSR	88	4.0	700
Yugoslavia	88	4.0	700

4.4 Mobile sources

The cost evaluation for mobile sources follows the same basic aproach as for stationary sources; however, due to structural differences slight modifications were necessary.

4.4.1 The algorithm for the cost evaluation

All costs and emission reductions are summed up over the whole lifecycle of the vehicles: The amount of abated NO_x emissions is calculated based on the emission factor for unabated emissions $nox_{i,j}$, the removal efficiency of the control option x_k, the average annual fuel consumption $fuel_{i,j,l}$ of a vehicle and its lifetime $lt_{i,j}$:

$$rnox_{i,j,k,l} = nox_{i,j}\, x_k^{NOx}\, fuel_{i,j,l}\, lt_{i,j} \tag{4.9}$$

The same calculations can be performed for the abatement of VOC and CO:

$$rvoc_{i,j,k,l} = voc_{i,j}\, x_k^{VOC}\, fuel_{i,j,l}\, lt_{i,j} \tag{4.10}$$

$$rco_{i,j,k,l} = co_{i,j}\, x_k^{co}\, fuel_{i,j,l}\, lt_{i,j} \tag{4.11}$$

The costs of applying control devices include the additional investments $ci^f_{i,j,k}$, increased maintenance costs f_i and the costs of potential replacements of parts of the control systems after its lifetime lt^{cat}:

$$OM_{i,j,k} = ci^f_{i,j,k} + (lt_{i,j,k} - 1) f_k + ci^f_{i,j,k} \frac{lt_{i,j}}{lt^{cat}_{i,j}} \tag{4.12}$$

Any (positive or negative) influence on fuel consumption is taken into account by:

$$OM^e_{i,j,k,l} = \lambda^e_{i,j,k}\, fuel_{i,j,l}\, c^e_{i,j,k,l}\, lt_{i,j} \tag{4.13}$$

The unit costs of abatement *ce* (related to one unit of fuel input) add up to

$$ce_{i,j,k,l} = \frac{OM_{i,j,k} + OM^{e}_{i,j,k,l}}{fuel_{i,j,k,l}\, lt_{i,j}} \tag{4.14}$$

If these costs are related to achieved emission reductions, again a measure for the cost efficiency of the control option will be obtained (f^x are the relative weights for the individual pollutants):

$$cn_{i,j,k,l} = \frac{ce_{i,j,k,l}}{rnox_{i,j}\, f^{NOx} + rvoc_{i,j}\, f^{VOC} + rco_{i,j}\, f^{CO}} \tag{4.15}$$

It should be mentioned that, in the present form, the factors leading to differences among countries are the annual energy consumption per vehicle and the fuel prices for the additional energy consumption. In reality, the average emission factors may also differ among countries according to the fleet composition and typical driving cycles. However, at the present time it does not seem feasible to obtain reliable data with respect to this item.

4.4.2 Data for cost calculation

In analogy to stationary sources international surveys on costs of pollution control equipment was the preferred data source for the RAINS model. Therefore, technology-specific data rely mainly on OECD surveys (OECD, 1988a; OECD, 1988b) and UN-ECE (1988a), and were modified to the specific requirements (Table 4.6) and (Table 4.7).

Table 4.6: Technology-specific data for mobile sources

		Heavy Duty Trucks		Gasoline Vehicles		
Parameter		U.S. 1988	U.S. 1991	EEC-compr.	U.S. 1985	Unit
NO_x removal efficiency	x_k	25	40	50	90	%
VOC removal efficiency	x'_k	0	0	50	90	%
CO removal efficiency	x''_k	0	0	50	90	%
lifetime of vehicles	lt_j, k	10	10	10	10	years
investment costs	ci^f	1200	2200	800	1000	DM/car
lifetime of catalyst	lt_k^{cat}	n.a.	n.a.	10	10	years
annual maintenance and overhead	f_k	10	15	0	0	% of total investm.
additional fuel consumption	λ_k^e	3	8	1.5	- 1.5	%

Table 4.7: Fuel prices (without taxes) and annual fuel consumption of mobile sources

	Fuel price		Fuel consumption	
Country	*Diesel*	*Gasoline*	*Diesel*	*Gasoline*
	[DM/MJ]		*[GJ/car/year]*	
Albania	10.90	12.85	400.	45.
Austria	12.85	13.99	790.	49.
Belgium	9.69	12.38	650.	45.
Bulgaria	10.90	12.85	400.	81.
CSSR	10.90	12.85	310.	30.
Denmark	11.82	11.63	520.	44.
Finland	13.47	19.16	780.	44.
France	9.32	9.37	840.	35.
FRG	8.77	10.80	640.	47.
GDR	10.90	12.85	150.	41.
Greece	7.11	8.92	390.	62.
Hungary	10.90	12.85	320.	49.
Ireland	13.22	13.04	600.	65.
Italy	9.88	11.81	600.	31.
Luxembourg	9.48	12.25	810.	49.
Netherlands	10.08	12.44	910.	43.
Norway	11.32	13.25	280.	45.
Poland	10.90	12.85	260.	35.
Portugal	11.42	13.59	840.	28.
Romania	10.90	12.85	400.	45.
Spain	9.88	11.19	490.	33.
Sweden	13.66	13.87	630.	55.
Switzerland	10.95	12.16	260.	52.
Turkey	13.14	20.51	400.	45.
UK	10.68	11.02	440.	54.
USSR	10.90	12.85	510.	58.
Yugoslavia	10.90	12.85	380.	31.

4.5 Cost coefficients for NO_x abatment

Using the parameters as presented in section 4.3.2, the evaluation of Equations 4.1 to 4.8 can be performed for all NO_x control options under consideration. Due to limited space, this paper will only list the abatement costs for the most important control options. However, a complete listing can be obtained by model runs.

If costs are related to electricity production, for SCR at new power stations using brown coal they vary between 0.69 and 0.95 DPf/kWh. The costs of SCR for new boilers using hard coal increase the costs of electricity generation between 0.55 and 0.82 Dpf/kWh. These estimates show good agreement with other published sources (e.g. Schärer and Haug, 1988). If these costs are related to the amount of NO_x removed, costs range for brown coal plants range from 2.83 to 3.87 DM/kg NO_x and for hard coal stations from 2.04 to 3.04 DM/kg NO_x (Table 4.8). These ranges in costs are caused by national differences in boiler size distributions and capacity utilization.

Introduction of the U.S. 1991 standard for heavy duty trucks would require costs in a range between 3.74 and 14.93 DM/kg NO_x (Table 4.9).

For the evaluation of the controlled three-way catalyst, the credit for simultaneous reductions of VOC and CO becomes of crucial importance. If no credit is given to the reduction of other pollutants, this technology is one of the more expensive options of controlling NO_x (with costs in a range between 3.72 and 10.58 DM/kg NO_x). However, if the side effects are also taken into account, it appears to be a very cost efficient solution (between 0.47 and 1.32 DM/kg of abated pollutant, if NO_x, VOC and CO are weighted equally).

The considerable variations in control costs of mobile sources among countries are caused by two factors:

- Differences in fuel prices (even if taxes are excluded).

Table 4.8: Costs of SCR for new brown coal (BC) and hard coal (HC) powerplants (PP) per kWh produced electricity and per kg NO_x removed

Country	*SCR, new BC PP*		*SCR, new HC PP*	
	DPf/kWh	*DM/kg* NO_x	*DPf/kWh*	*DPf/kg* NO_x
Albania	0.80	3.31	0.59	2.18
Austria	0.87	3.87	0.63	2.33
Belgium	0.94	3.33	0.66	2.44
Bulgaria	0.75	3.09	0.55	2.04
CSSR	0.75	3.09	0.55	2.04
Denmark	n.a.	n.a.	0.64	2.35
Finland	n.a.	n.a.	0.82	3.04
France	0.83	3.41	0.58	2.16
FRG	0.69	2.83	0.60	2.23
GDR	0.75	3.09	0.55	2.04
Greece	0.70	2.86	0.60	2.23
Hungary	0.78	3.22	0.57	2.12
Ireland	n.a.	n.a.	0.61	2.24
Italy	0.90	3.70	0.57	2.10
Luxembourg	n.a.	n.a.	0.63	2.33
Netherlands	n.a.	n.a.	0.61	2.33
Norway	n.a.	n.a.	n.a.	n.a.
Poland	0.78	3.20	0.57	2.10
Portugal	0.83	3.43	0.59	2.17
Romania	0.78	3.20	0.57	2.11
Spain	0.74	3.06	0.56	2.07
Sweden	n.a.	n.a.	0.53	1.97
Switzerland	n.a.	n.a.	0.61	2.25
Turkey	0.75	3.08	0.71	2.62
UK	n.a.	n.a.	0.57	2.11
USSR	0.73	3.01	0.54	2.00
Yugoslavia	0.91	3.74	0.74	2.74

- Differences in annual fuel consumption per car. As listed in table 4.9, major variations of this variable exist for Europe.

Due to the limited accuracy of the underlying statistics (especially on the number of registered vehicles in Europe, including off-road vehicles), the magnitude of the observed variations could be questioned. Nevertheless it seems reasonable to introduce such differences rather than ignore them.

4.6 National cost curves for NO_x abatement

As demonstrated above, national circumstances result in variations of the costs for applying the same control technology over Europe. However, these differences are not the only ones causing different costs of abatement strategies. Another source of variations is related to the structural differences of national energy systems which determine the potential for application of individual control options. One way to analyse the combined effect of these two factors is the compilation of 'national cost curves' for NO_x abatement. These curves display the lowest costs for achieving varying reduction levels, applying the cost optimal combination of abatement options. In theory, they can be identified by repeated cost-optimization runs stepwise, changing overall reduction levels. A faster method, however, will rank the available control options according to their marginal costs for NO_x reduction and link their individual potentials for emission removal.

Because the overall potential of reducing emission from a specified source has to be consistent, special provisions have to be taken for control options excluding each other (e.g. the uncontrolled catalysts and the controlled three-way system for mobile sources). In these cases, the marginal costs to be taken into account for the more expensive but also more efficient control option have to be related to the incremental emission reductions compared to the cheaper option.

Table 4.9: Costs of introducing U.S. Norm 1991 for heavy duty trucks and for 3-way catalysts for gasoline fueled cars (per kg of NO_x abated)

Country	*U.S. Standard 1991*	*3-way catalyst*	
	DM/kg NO_x	*DM/kg* NO_x	*DM/kg* NO_x
		no credit for VOC and CO	*credit for VOC and CO*
Albania	6.65	6.69	0.87
Austria	4.49	5.74	0.72
Belgium	4.55	6.31	0.79
Bulgaria	6.65	3.72	0.47
CSSR	8.09	10.58	1.32
Denmark	5.64	6.48	0.81
Finland	4.62	6.31	0.79
France	3.80	8.26	1.03
FRG	4.46	6.06	0.76
GDR	14.93	7.66	0.96
Greece	6.19	4.58	0.57
Hungary	7.89	6.35	0.80
Ireland	5.35	4.27	0.54
Italy	4.83	9.30	1.16
Luxembourg	3.91	5.77	0.72
Netherlands	3.74	6.61	0.82
Norway	8.84	6.29	0.79
Poland	9.32	9.02	1.13
Portugal	4.12	10.28	1.29
Romania	6.65	6.95	0.87
Spain	5.58	8.73	1.09
Sweden	5.26	5.08	0.64
Switzerland	9.33	5.43	0.68
Turkey	6.99	6.13	0.77
UK	6.16	5.24	0.66
USSR	5.58	5.32	0.67
Yugoslavia	6.91	10.23	1.29

This formally correct and mathematically necessary procedure has important effects for the compilation of national cost curves. In the event that exclusive control options with different costs and removal rates exist for a source, the ranking procedure will consider the incremental marginal costs for the more expensive technology, which are greater than the original unit costs of abatement for this option. Therefore, the introduction of such control options will have less priority compared to a situation where the less efficient options would not have been introduced at all.

Again, this effect is of relevance for evaluation of the three-way catalyst. If no credit is given for simultaneous reductions of VOC and CO, in some countries the additional NO_x removals of the three-way system (over the reduction achievable by uncontrolled catalysts) are very expensive. The three-way system is therefore ranked into the very expensive group of options. If, on the other hand, the uncontrolled catalyst would not have been considered in the procedure, the introduction of the three-way system would have lower unit and marginal costs and would therefore be ranked higher.

The Appendix contains cost curves of NO_x reduction for all European countries, if the official forecasts of energy consumption for the year 2000 are taken as a basis. The two curves describe marginal and total costs of abatement. For these examples, no credit is given to simultaneous reduction of CO and VOC.

4.7 Current reduction plans and maximum feasible reductions

The data can also be used to analyse the control cost which are implied by the Sofia Protocol on NO_x emissions (UN-ECE, 1988a). Although countries may, according to the protocol, select any year between 1980 and 1987 as their reference year for NO_x reductions, due to lack of information 1980 was taken as the reference year. The aim of the protocol is to reach the

Table 4.10: Assumption of 'Best Available Technologies' in different economic sectors

Sector	Best Available Technology	Removal Efficiency
Powerplants	Combustion Modification + SCR	90 %
Industry	Combustion Modification + SCR Processes	90 %
Refineries	Combustion Modification + SCR Processes	90 %
Heavy Duty Trucks	U.S.-Standard 1991	40 %
Gasoline Cars	3-way catalyst	80 %
Industrial Process Emissions	Different Methods	80 %

specified levels by 1994; for reasons of comparability the projected energy consumption of the year 2000 was selected as the basis for the cost evaluation. Although 12 countries committed a 30 percent reduction and 8 others a standstill by 1994, the total European NO_x emissions can be expected to decline by only 5 percent, because countries with high expectations on economic growth (mainly in Southern Europe) will increase emissions to balance out some of the reductions. Table 4.11 displays the emissions after implementation of the currently committed control measures.

The maximum technically feasible reductions apply the most efficient control technologies without changing the energy consumption itself (e.g. by energy conservation, fuel substitution, speed limits). For this scenario, the assumptions shown in Table 4.10 were made.

Table 4.11: NO_x emissions (in kt NO_x/year) after implementation of the Current Reduction Plans and the Maximum Technically Feasible Reductions.

Country	*Current Reduction Plans*		*Maximum Feasible Reductions*	
	kt NO_x	*% Reduction*	*kt* NO_x	*% Reduction*
Albania	46	*+64*	16	*43*
Austria	167	*30*	103	*57*
Belgium	307	*30*	181	*59*
Bulgaria	357	*0*	198	*45*
CSSR	628	*0*	214	*73*
Denmark	175	*30*	85	*66*
Finland	163	*30*	121	*49*
France	1360	*30*	674	*66*
FRG	2023	*30*	953	*67*
GDR	850	*0*	252	*70*
Greece	435	*+82*	132	*45*
Hungary	252	*18*	110	*46*
Ireland	117	*+31*	37	*58*
Italy	1020	*30*	678	*55*
Luxembourg	22	*30*	16	*49*
Netherlands	403	*30*	229	*60*
Norway	118	*30*	87	*49*
Poland	1597	*0*	551	*65*
Portugal	255	*51*	88	*40*
Romania	851	*+29*	335	*50*
Spain	950	*0*	538	*44*
Sweden	233	*30*	142	*58*
Switzerland	130	*30*	61	*67*
Turkey	1040	*+192*	514	*+44*
UK	2324	*0*	838	*64*
USSR	9454	*0*	3678	*61*
Yugoslavia	574	*+45*	184	*53*
Total	25854	*5*	11027	*60*

Table 4.12 lists the costs of achieving the specified emission levels of Table 4.11. Following the protocol, countries have committed emission reductions without specifying how they will attain these targets. Therefore, the cost estimate for the current reduction plans could only be based on the assumption of a cost optimal combination of reduction measures as computed by the national cost curves. However, in reality countries could also achieve these reductions by sub-optimal combinations, resulting in higher costs.

According to this estimate, the total European cost implied by the current reduction plans would amount to 4.5 billion DM/year. This is roughly 40 percent of the expenditures necessary to reach the sulfur reductions currently committed. However, the maximum technically feasible reduction of NO_x resulting in an overall emission decline of 60 percent would cost 66.3 billion DM/year.

Table 4.12: Abatement costs (in million DM/year) for the Current Reduction Plans (CRP) and the Maximum Technically Feasible Reductions (MFR)

	CRP 10^6 *DM/year*	MFR 10^6 *DM/year*
Albania	0	106
Austria	71	436
Belgium	114	888
Bulgaria	158	1291
CSSR	0	1703
Denmark	79	706
Finland	249	637
France	481	2651
FRG	523	5509
GDR	0	2691
Greece	0	924
Hungary	0	646
Ireland	0	193
Italy	1316	3606
Luxembourg	9	31
Netherlands	135	1054
Norway	169	512
Poland	0	3922
Portugal	0	508
Romania	0	2276
Spain	553	3116
Sweden	91	535
Switzerland	53	279
Turkey	0	2357
UK	256	5289
USSR	316	22468
Yugoslavia	0	2023
Total	4578	66371

Chapter 5

Conclusions

Several factors cause variations in the potential and costs for control of NO_x emissions among European countries. Based on an European emission inventory for nitrogen oxides, these differences can be explored and analyzed. The emission inventory computes anthropogenic NO_x emissions from energy combustion and industrial activities based on common emission factors for 8 fuel types and 5 combustion sectors.

A variety of options for control of NO_x emissions is presently available. However, this economic analysis is restricted to the most important methods which do not require structural changes in energy consumption. For stationary sources, combustion modifications and selective catalytic reduction (SCR) are used. NO_x emissions from heavy duty trucks can be reduced by two stages of reduction measures complying with the U.S. Norm 1988 and 1991. For gasoline cars, the use of controlled and uncontrolled catalysts is considered.

Several factors create variations of control costs among countries. Besides the structual differences in energy consumption for stationary sources, the annual capacity utilization and the average boiler size have the greatest influence on actual abatement costs. For the same control technology, typical variations up to 20 percent can be expected.

The control costs for mobile sources are sensitive to the average fuel consumption (as a surrogate for the size composition of the fleet and the mileage driven) and national differences in fuel price. The resulting variations are larger for mobile sources than for stationary sources; however, at present some uncertainty about the accuracy of the underlying statistical material cannot be completely eliminated.

The cost efficiency of some control options is crucially related to the credit given to simultaneous removal of pollutants other than NO_x. If NO_x removal is considered separately, such abatement technologies appear to be relatively expensive. However, in an integrated context, if all pollutants are taken into account, they become extremely cost efficient. Since at the present time no general guideline on how to weight different substances has been accepted, no final evaluation can be performed yet.

An analysis of the currently committed reductions of NO_x emissions results in an expected decline of 5 percent over the whole of Europe. If countries would follow a pure cost minimizing principle, the involved annual expenditures can be estimated to be 4.5 billion DM per year. This amounts to roughly 40 percent of the costs for sulfur reductions presently annouced. A maximum technically feasible reduction could reduce the European NO_x emissions by some 60 percent. The incurred costs would increase to 66 billion DM/year.

The analysis of international potential and costs for NO_x abatement opens the possibility of evaluating the cost efficiency of different control strategies. Furthermore, the analysis also provides an important input for designing receptor-oriented control strategies that allocate emission reductions spatially to attain prespecified regional deposition levels for nitrogen in cost optimal ways. However, an integrated analysis should also consider the contribution of ammonia to total nitrogen deposition.

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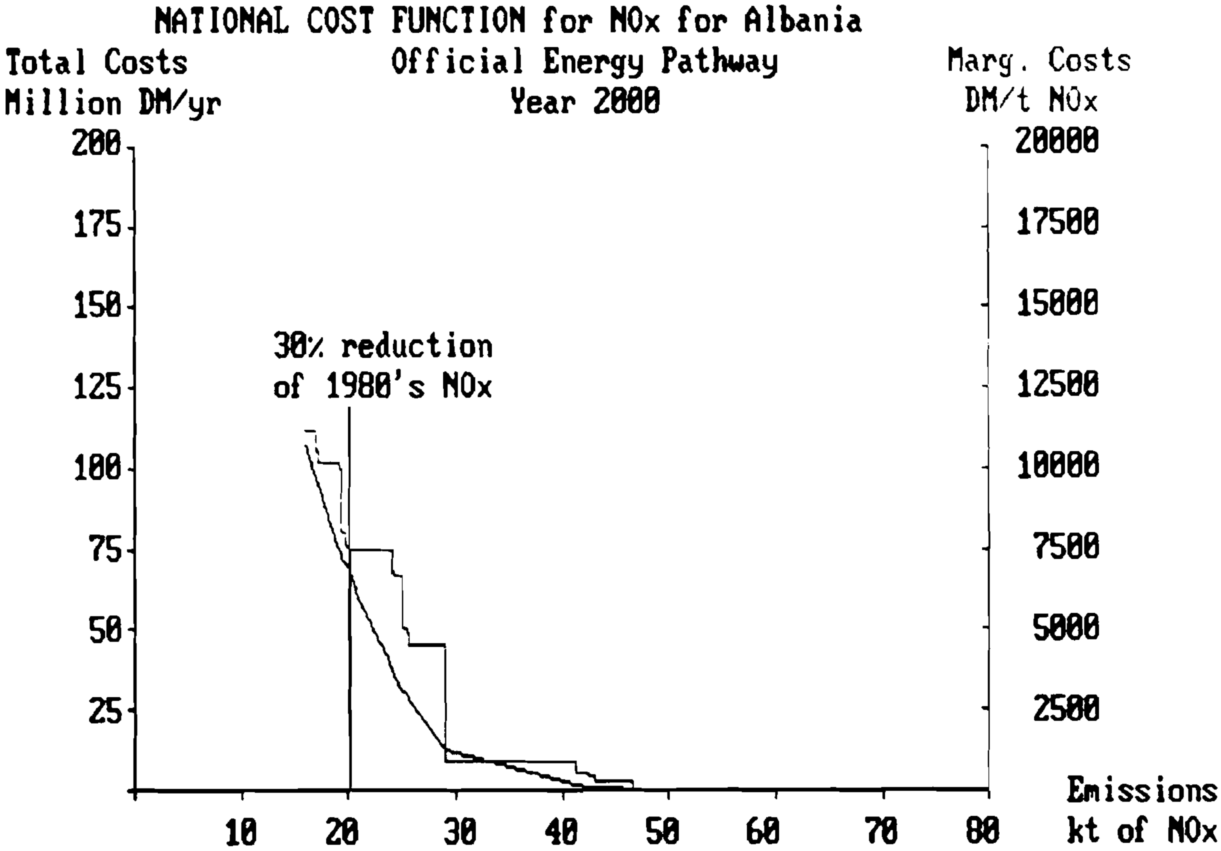
APPENDIX

The appendix contains national cost curves for the abatement of NO_x emissions in Europe. These calculations are based on the forecast energy consumption of the year 2000 and exclude energy conservation and fuel substitution. In this example case, no credit is given to simultaneous reduction of other pollutants such as CO and VOC.



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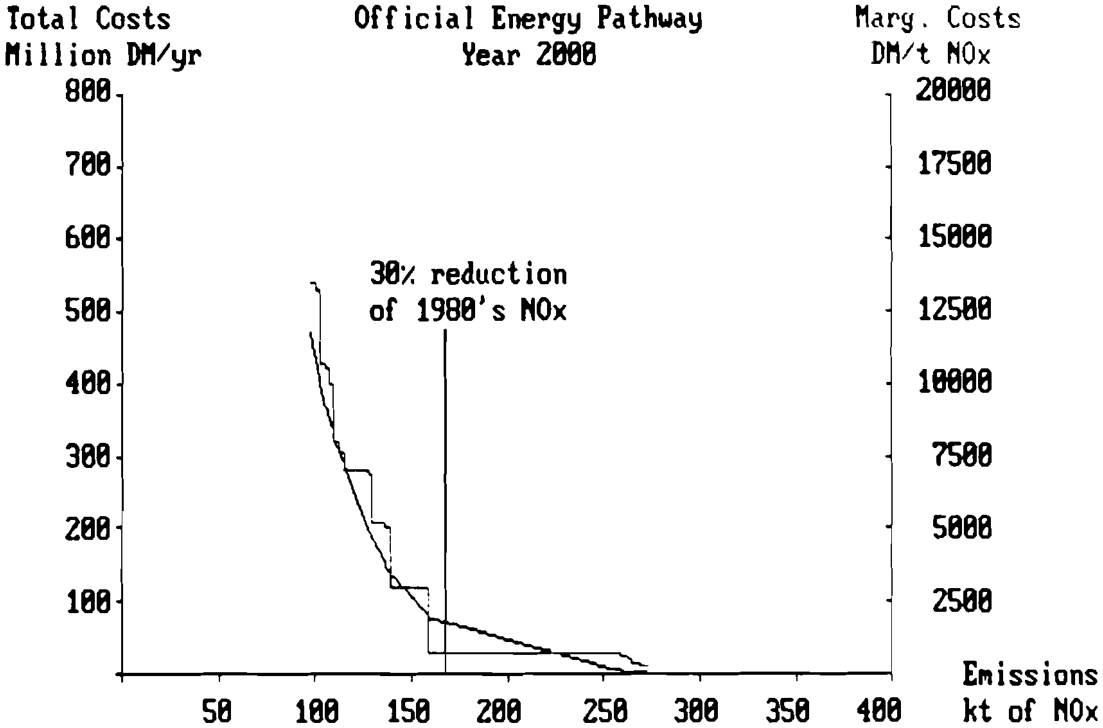

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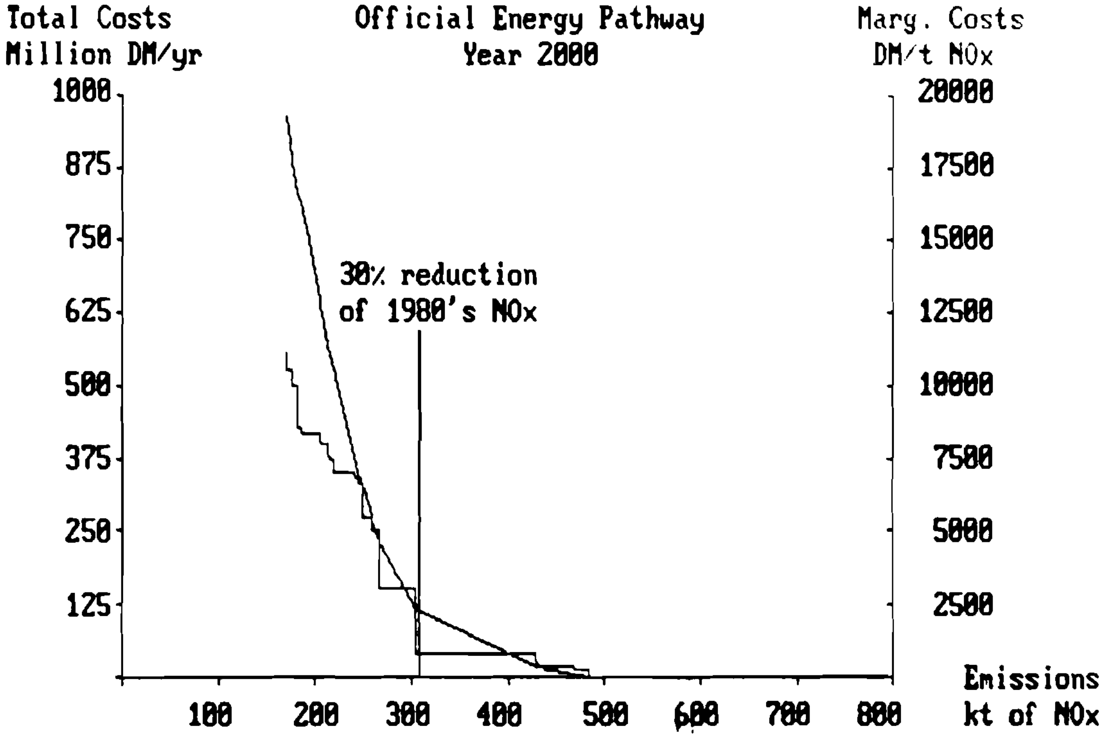

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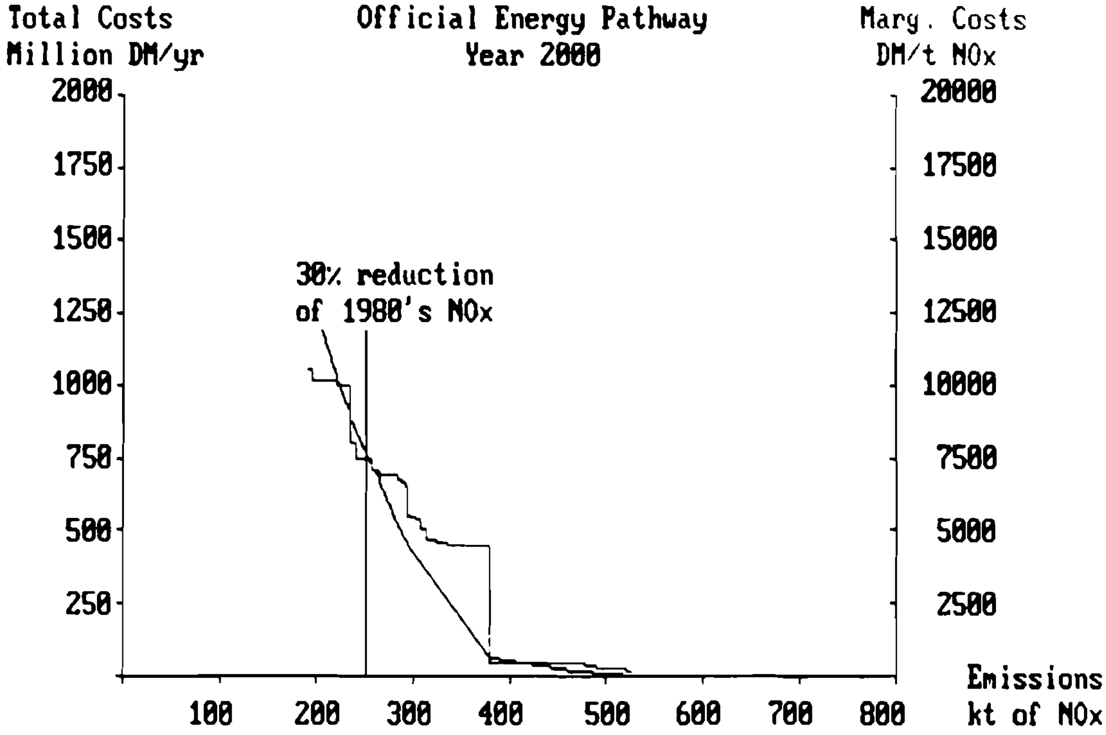

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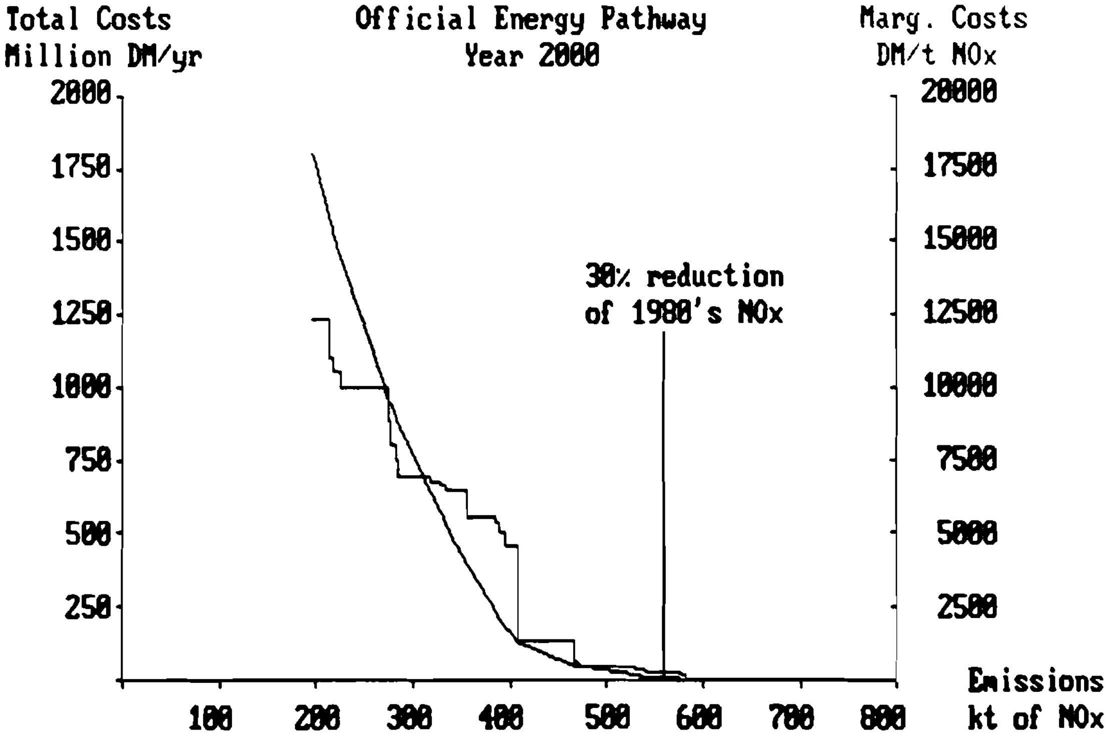

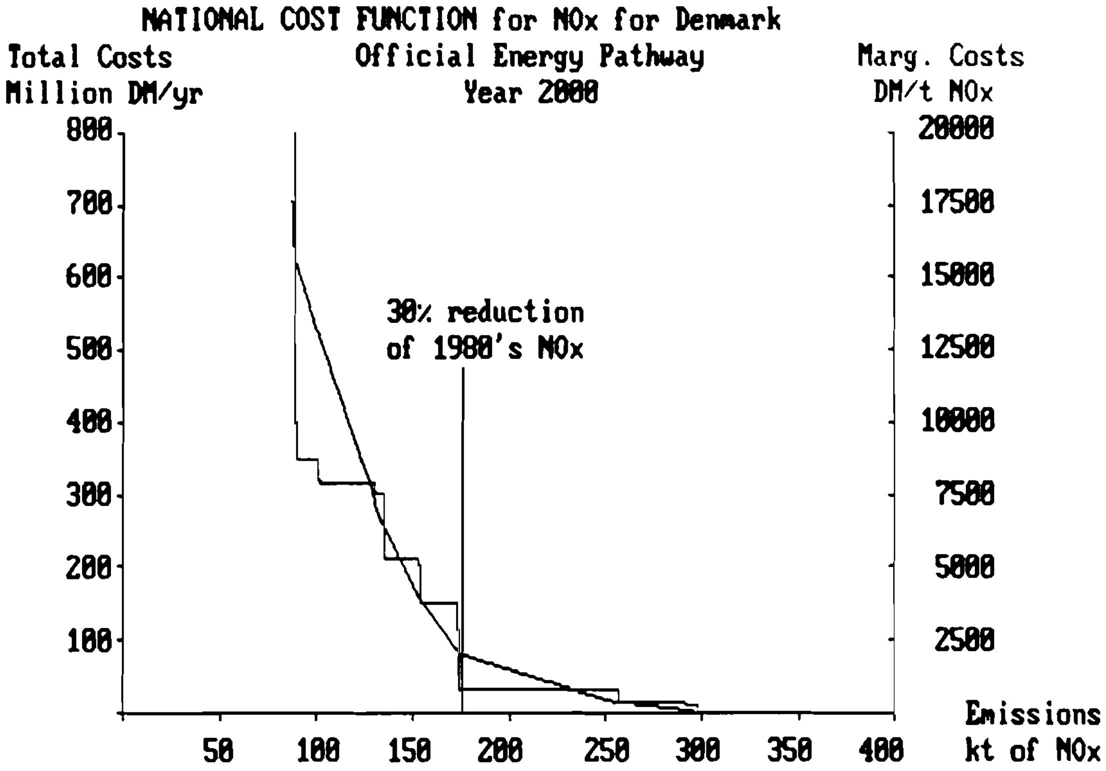
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Marg. Costs
DM/t NOx
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200
100
20000
17500
15000
12500
10000
7500
5000
2500
30% reduction
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100
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200
250
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350
400
Emissions
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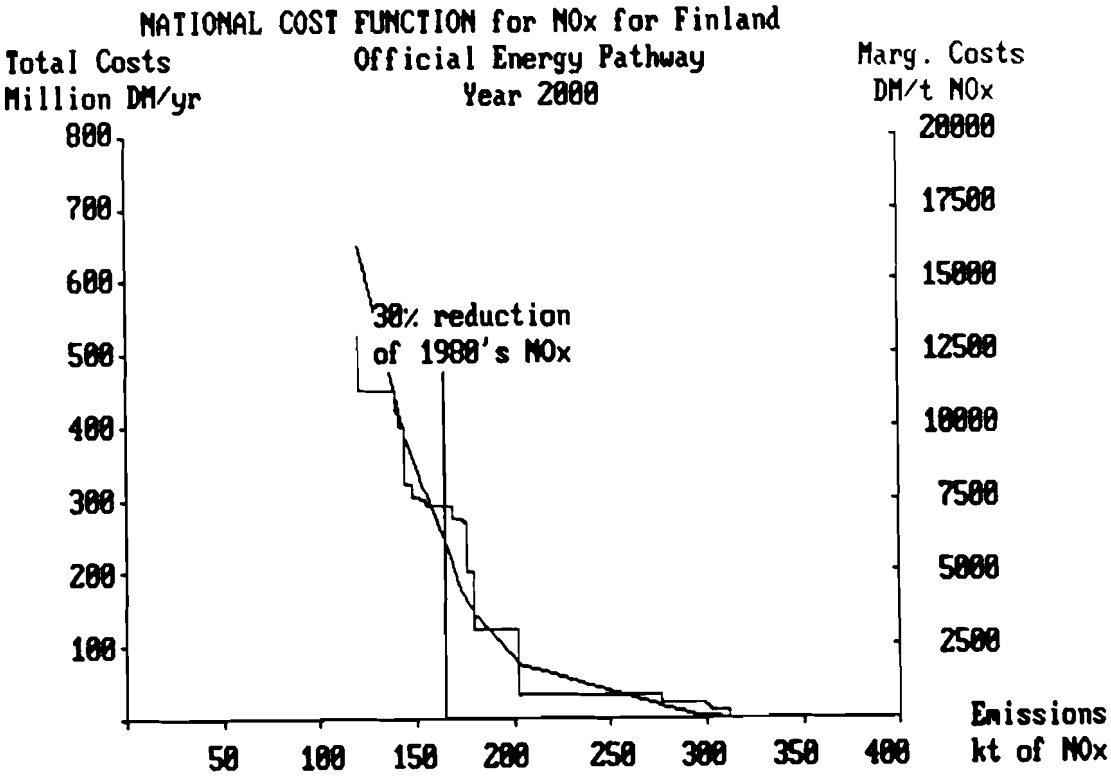
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Marg. Costs
DM/t NOx
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700
600
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200
100
20000
17500
15000
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30% reduction
of 1980's NOx
50
100
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250
300
350
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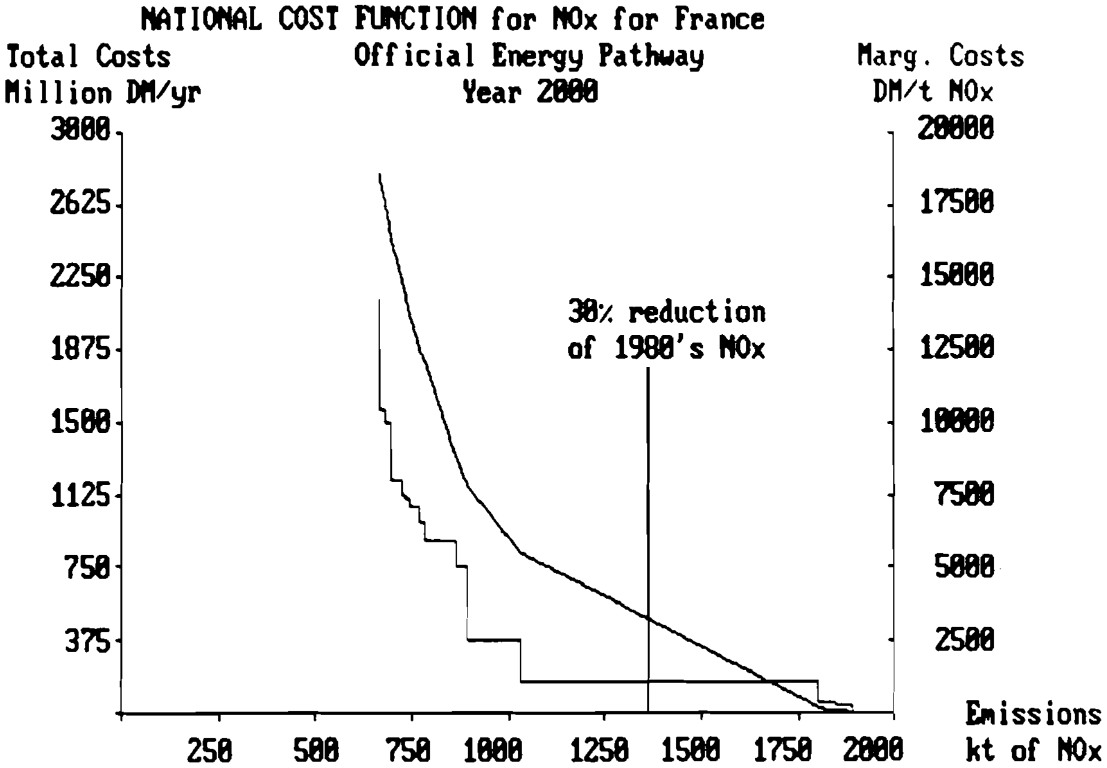
Emissions
kt of NOx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15000
12500
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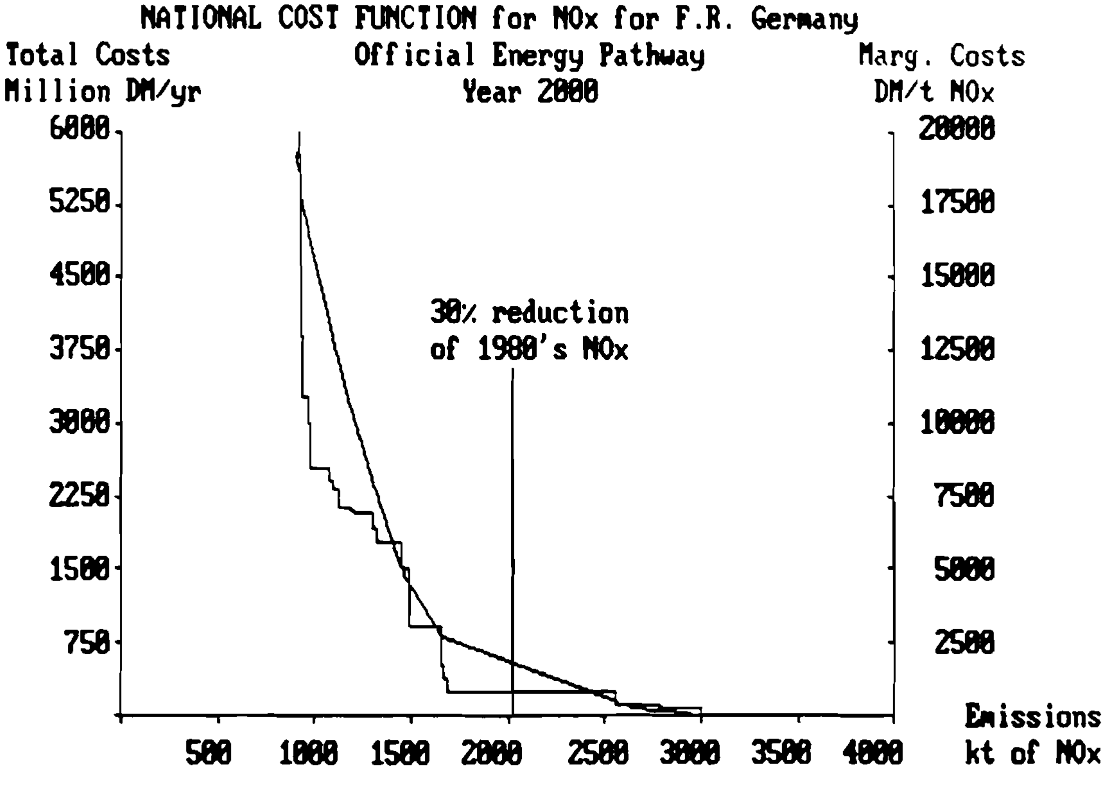
1750
2000
Emissions
kt of NOx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Marg. Costs
DM/t NOx
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17500
15000
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10000
7500
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30% reduction
of 1980's NOx
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4000
Emissions
kt of NOx

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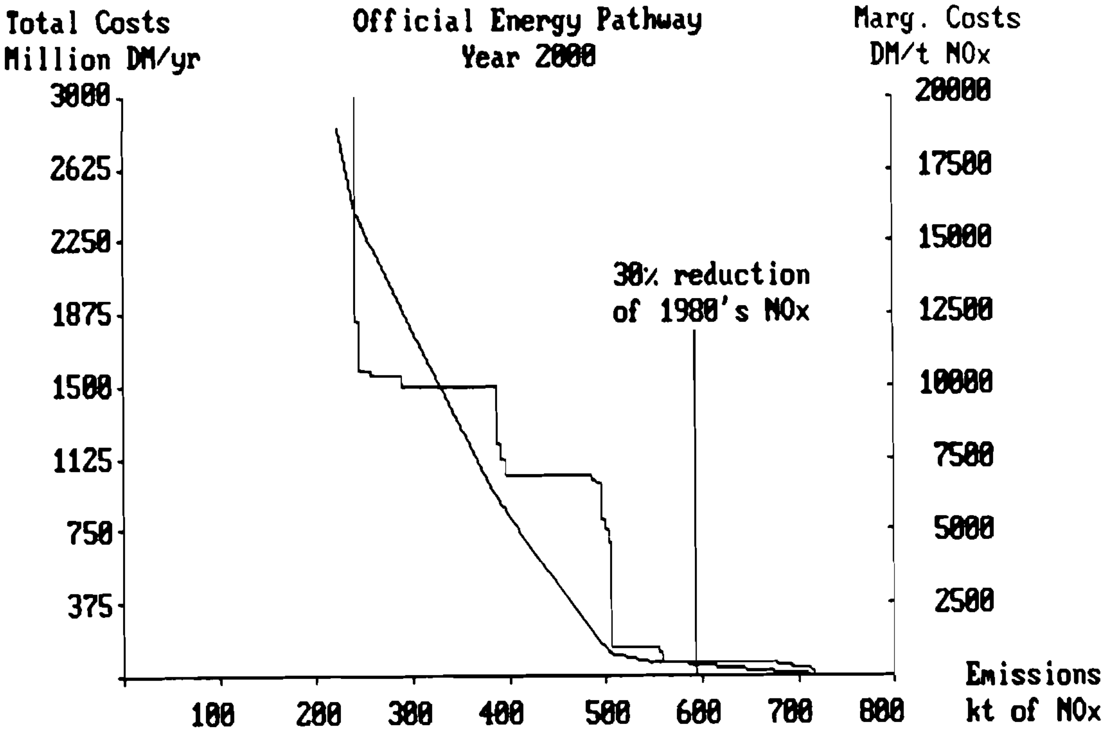

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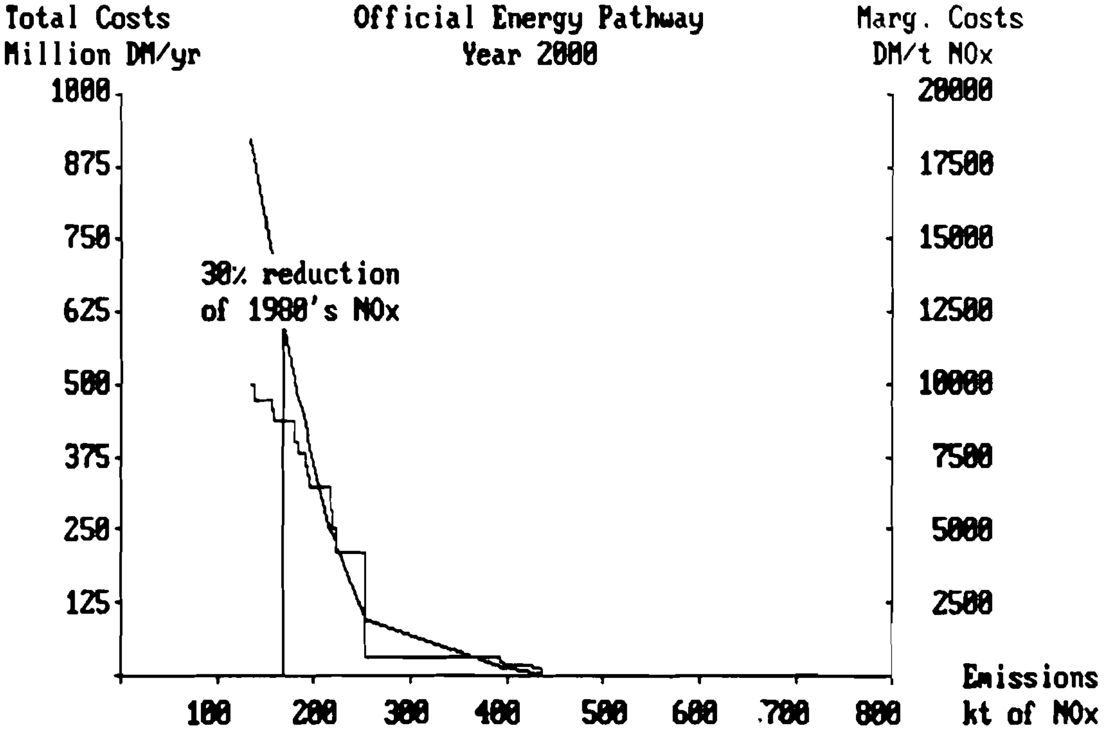

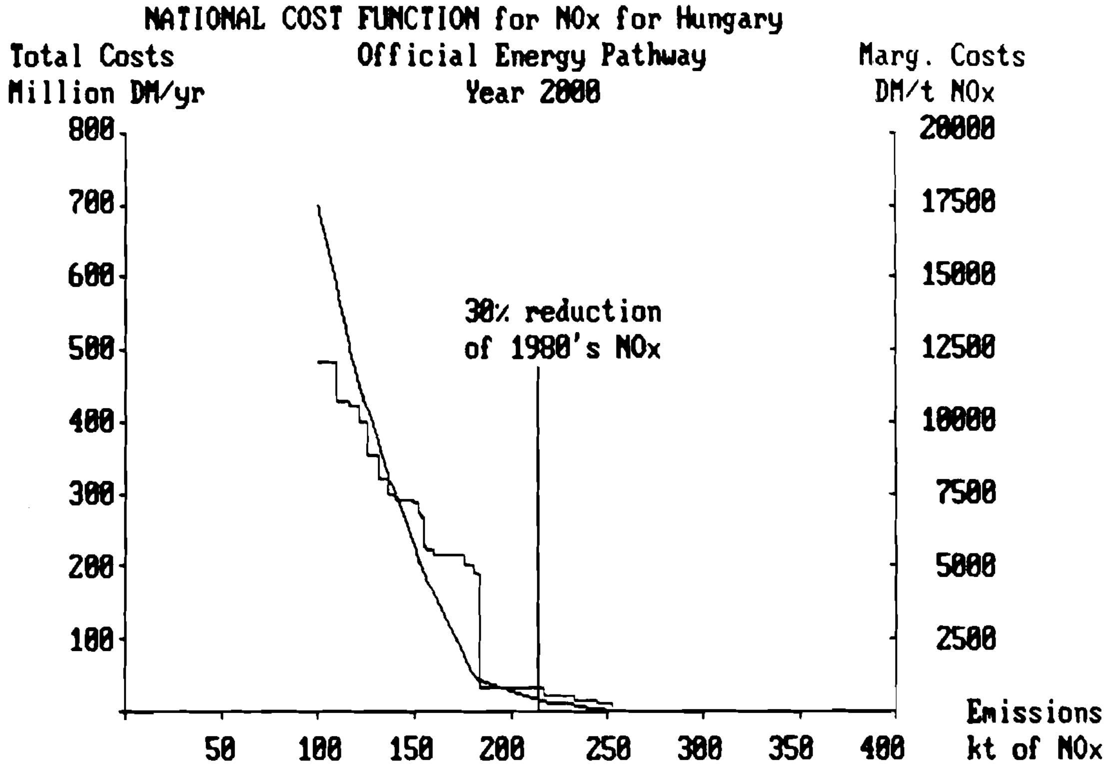
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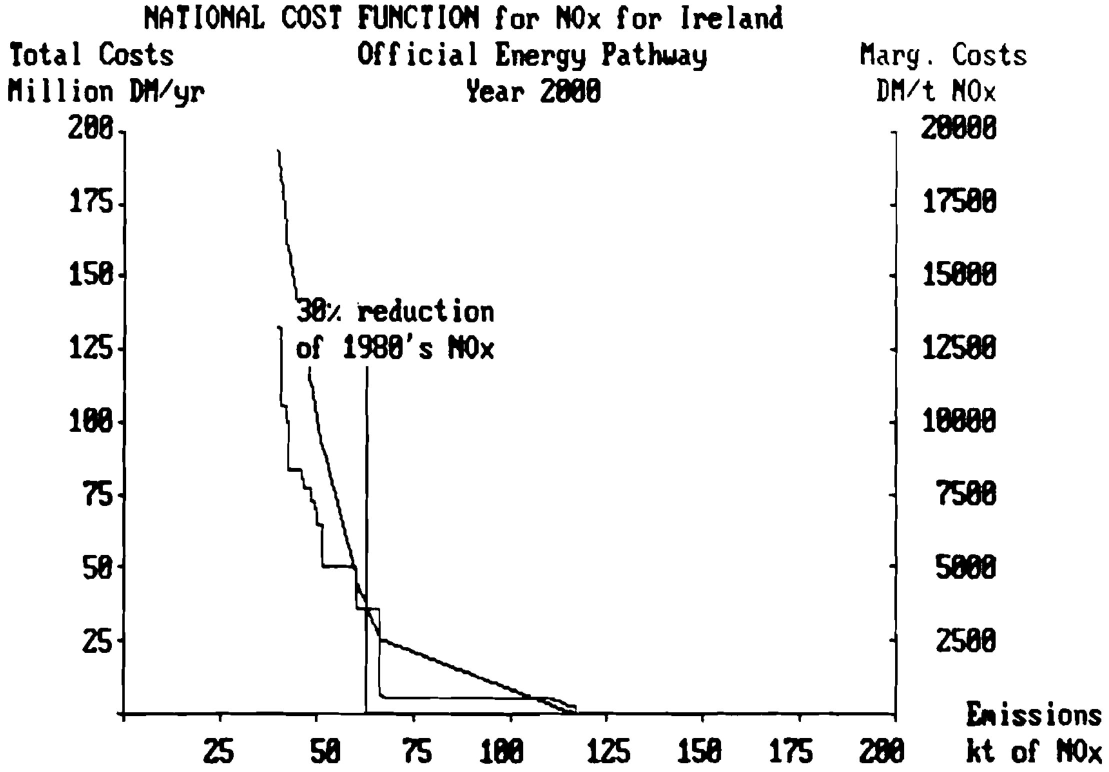
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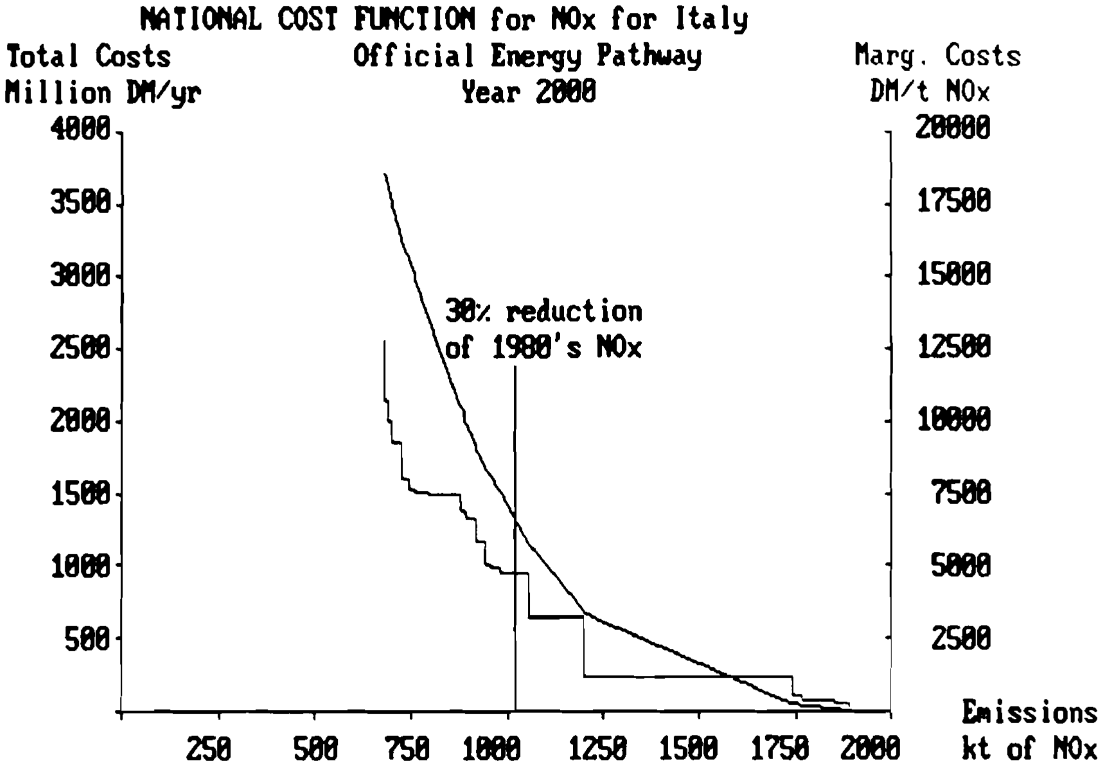
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Million DM/yr
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Marg. Costs
DM/t NOx
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3000
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20000
17500
15000
12500
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30% reduction
of 1980's NOx
250
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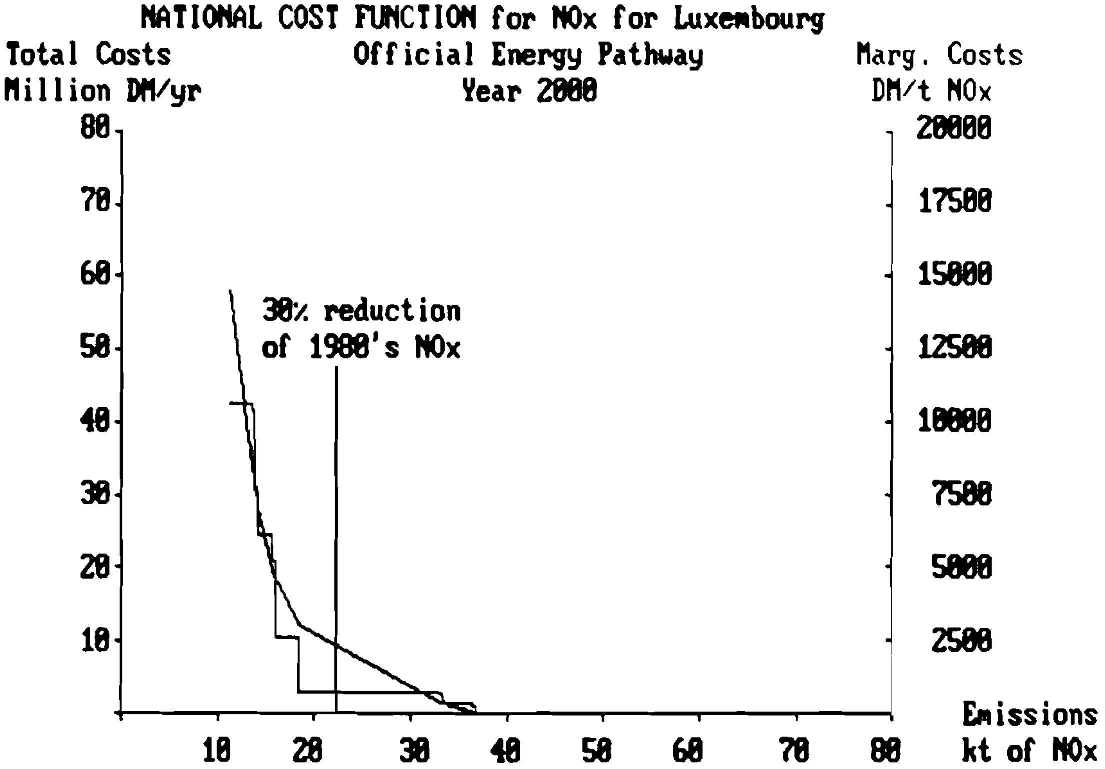
2000
Emissions
kt of NOx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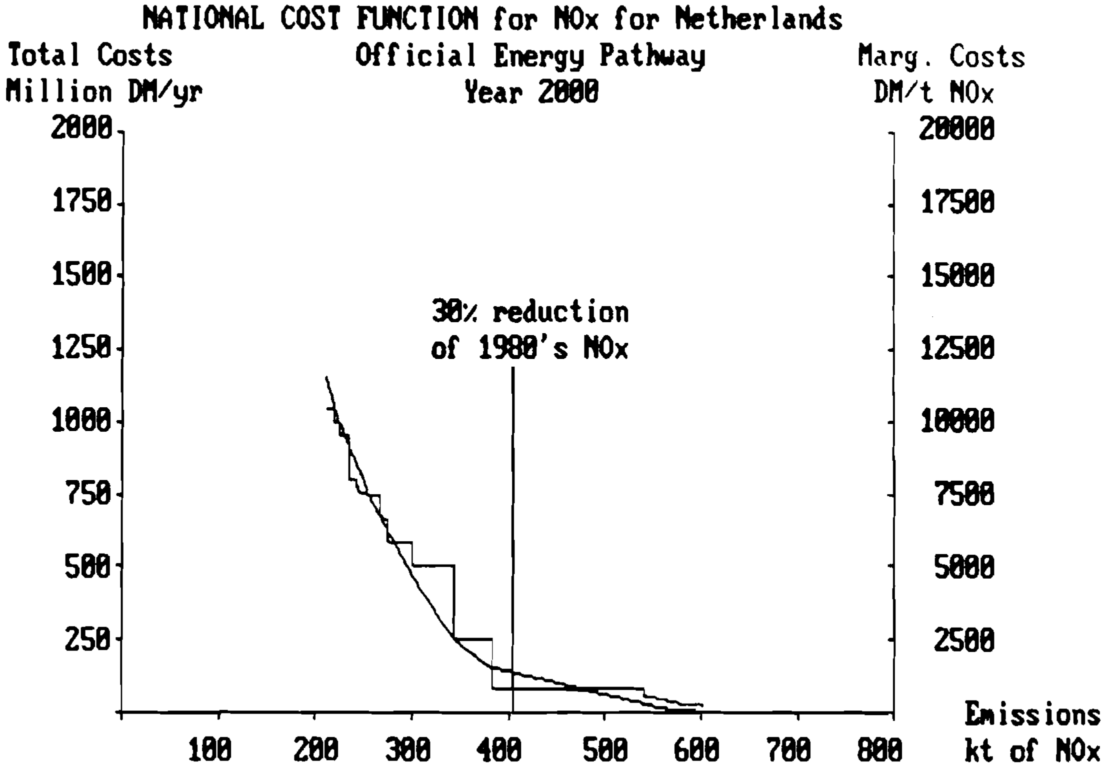
80
Emissions
kt of NOx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Marg. Costs
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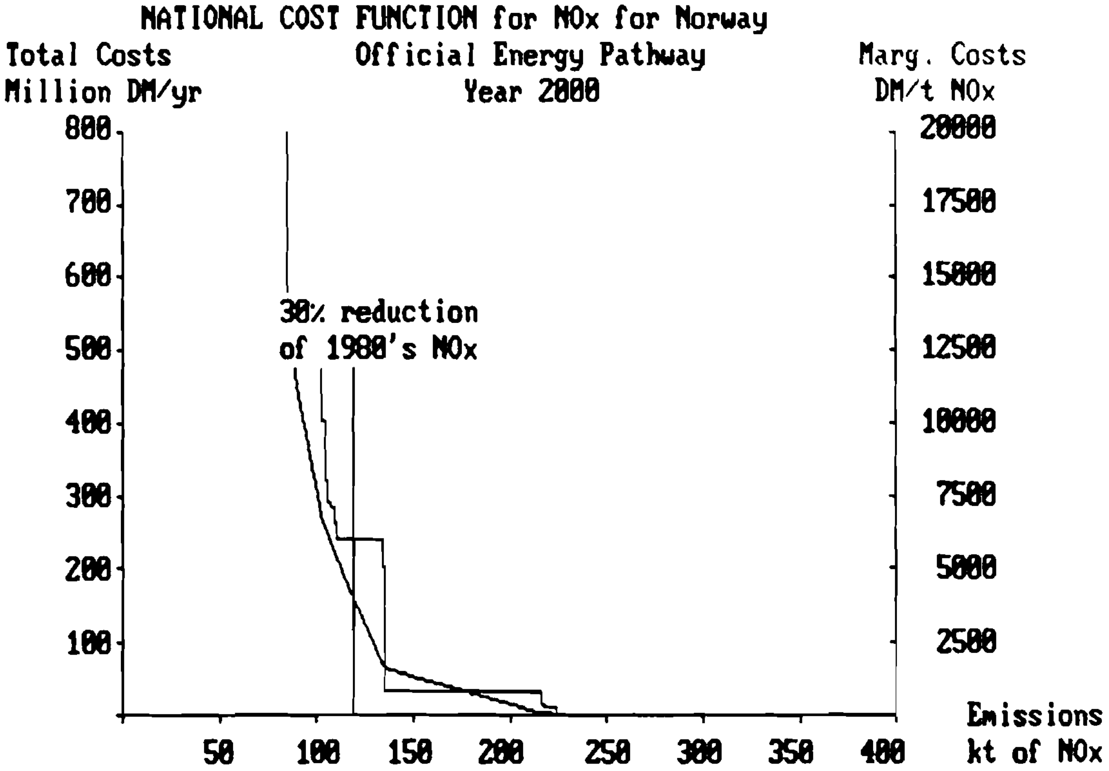
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Million DM/yr
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7500
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30% reduction
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Emissions
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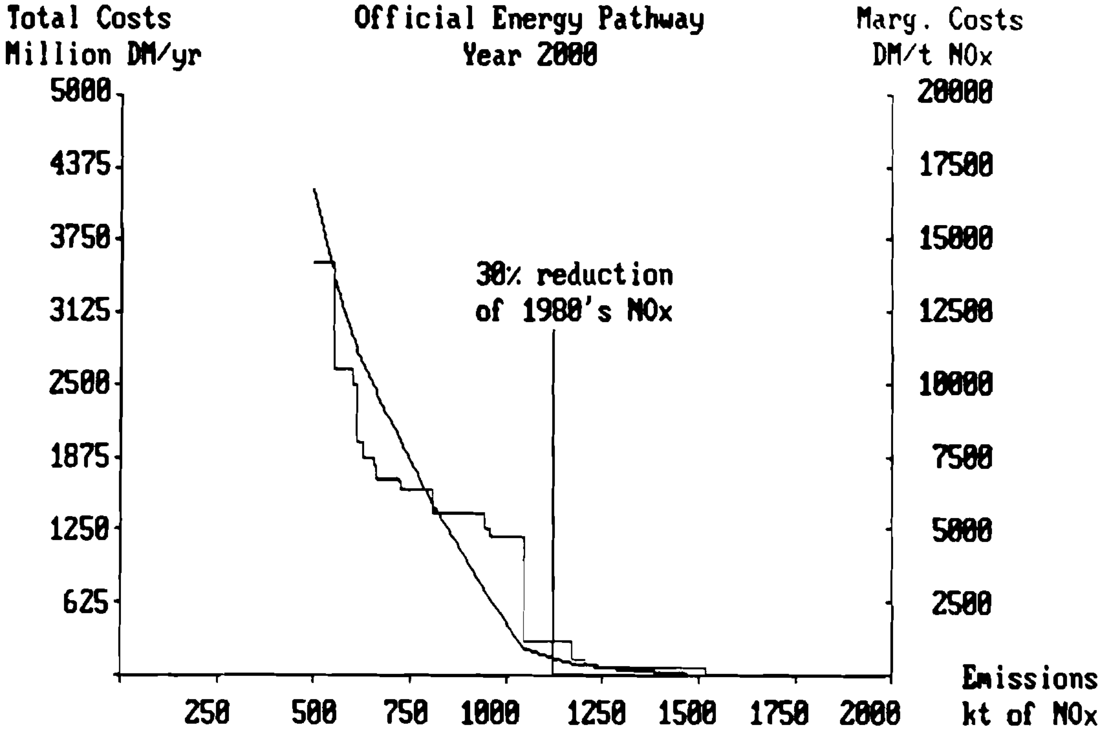

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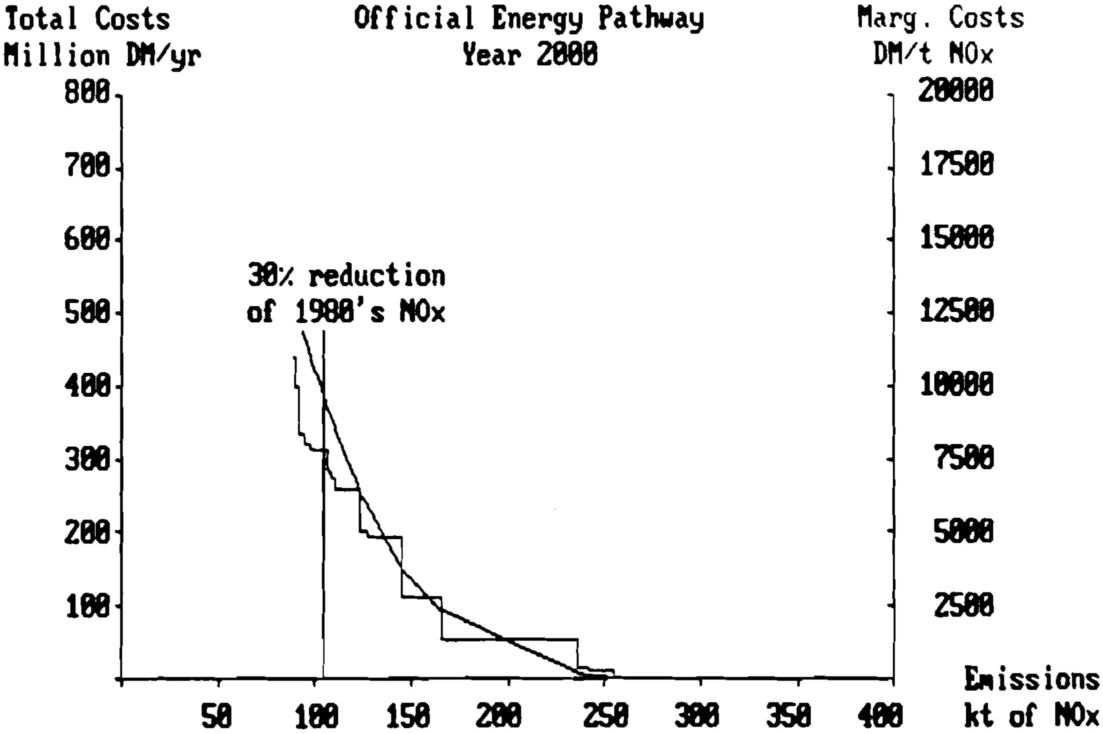

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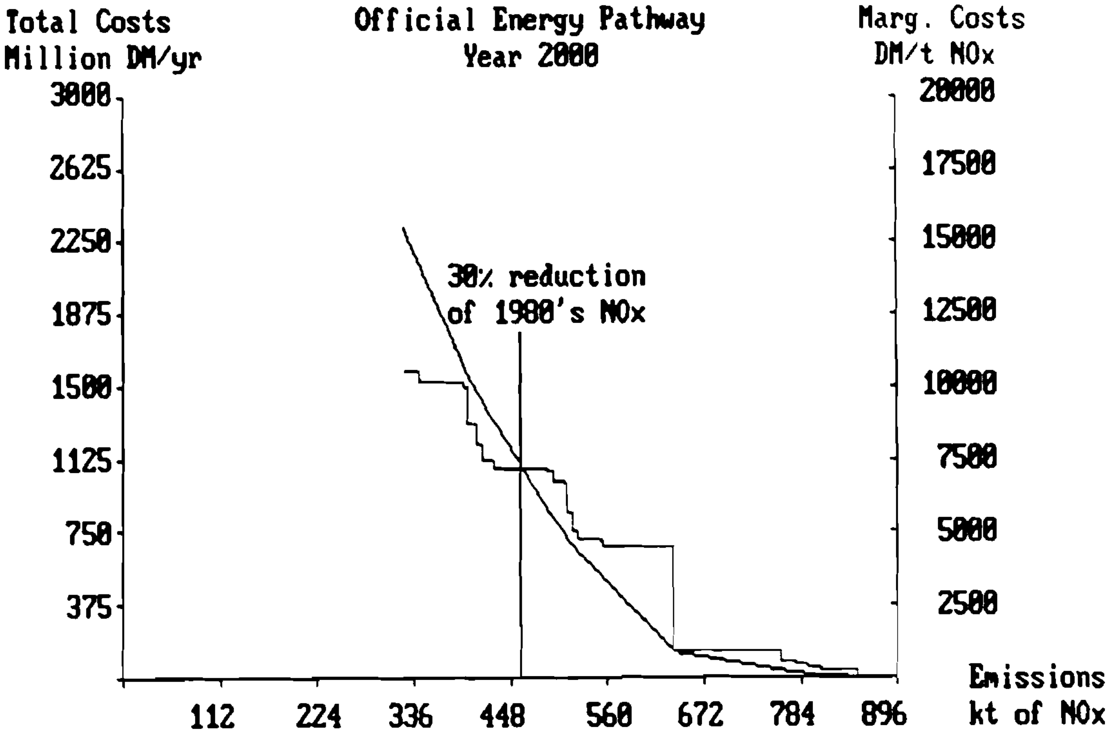
Official Energy Pathway

Year 2000



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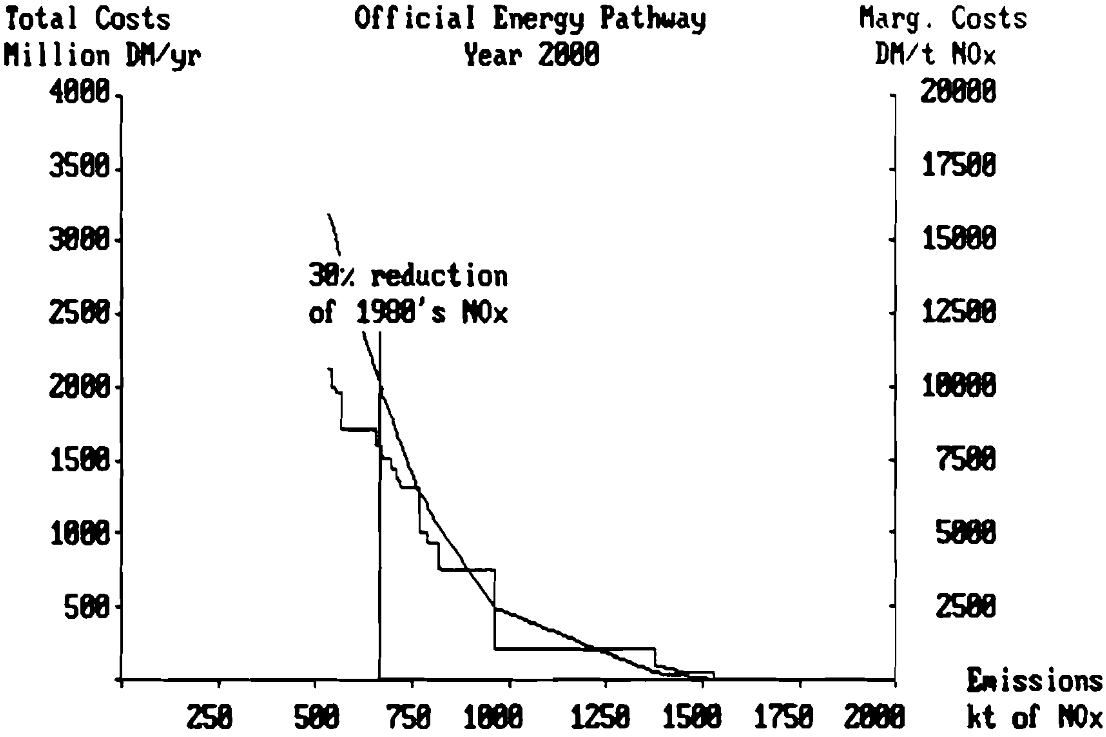
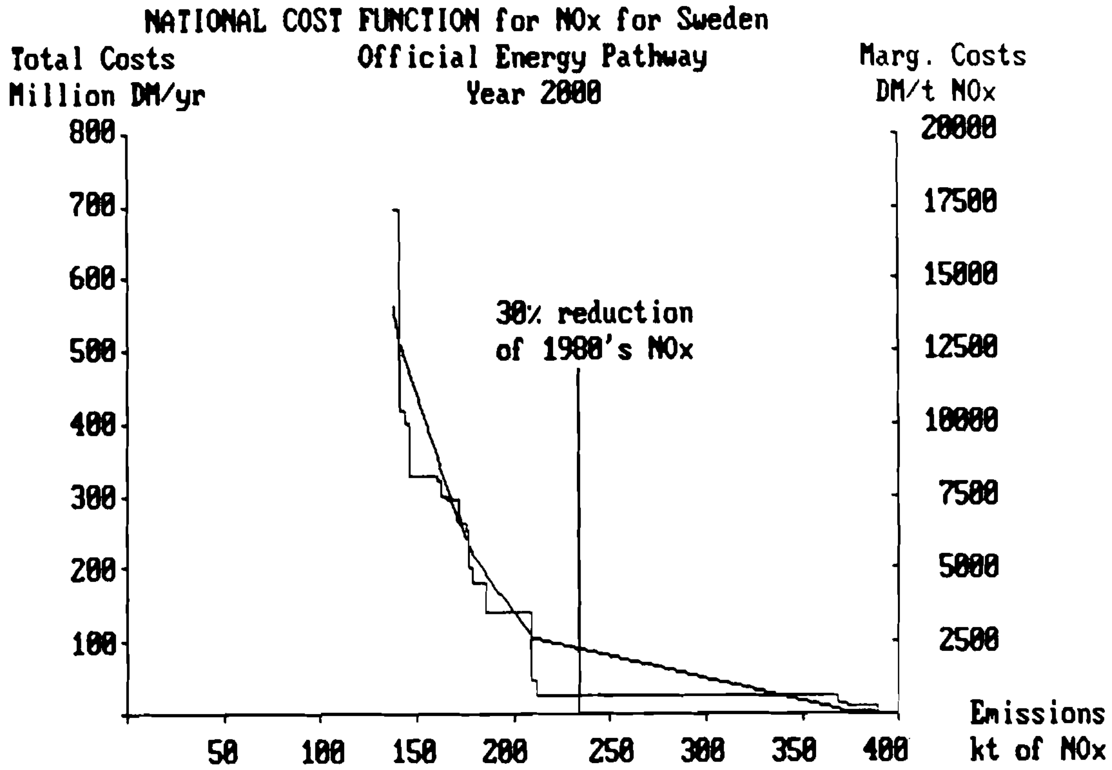
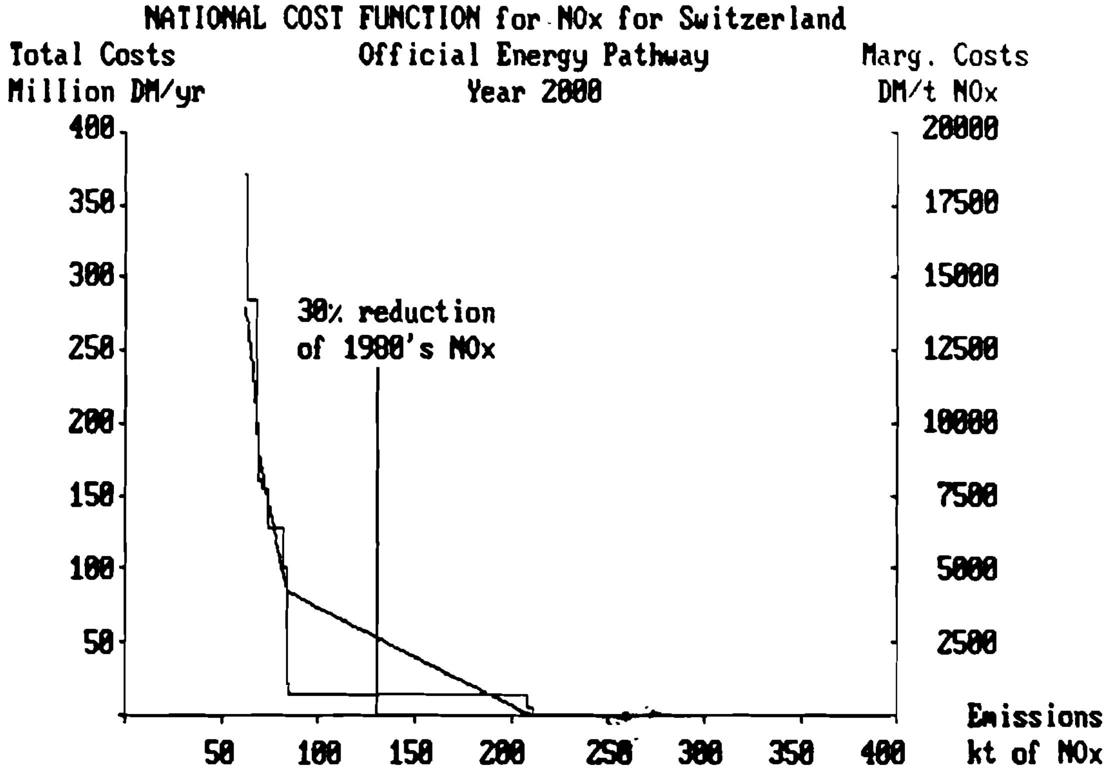
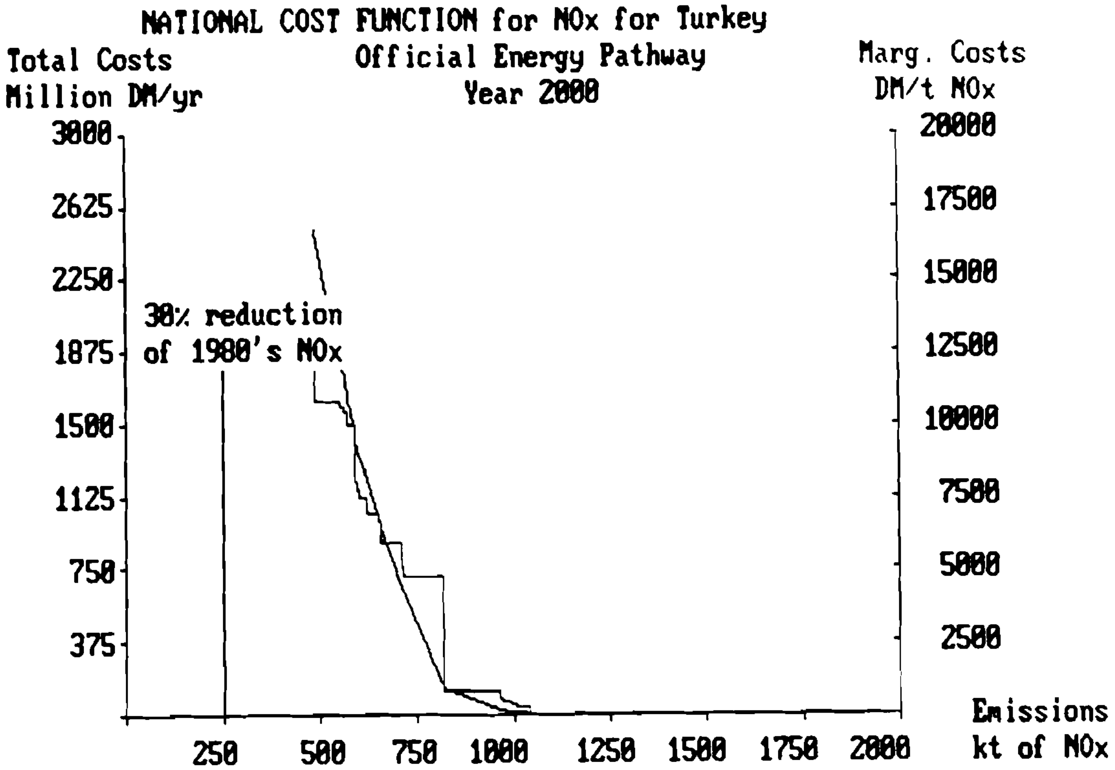
Official Energy Pathway

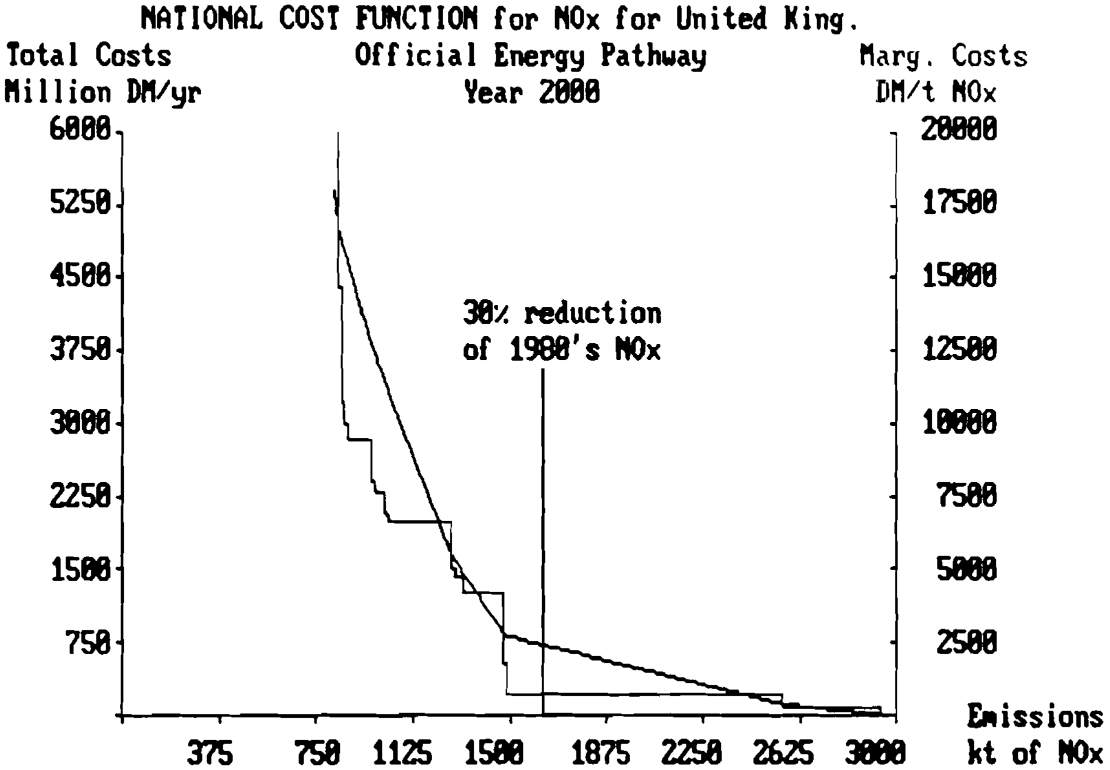
Year 2000

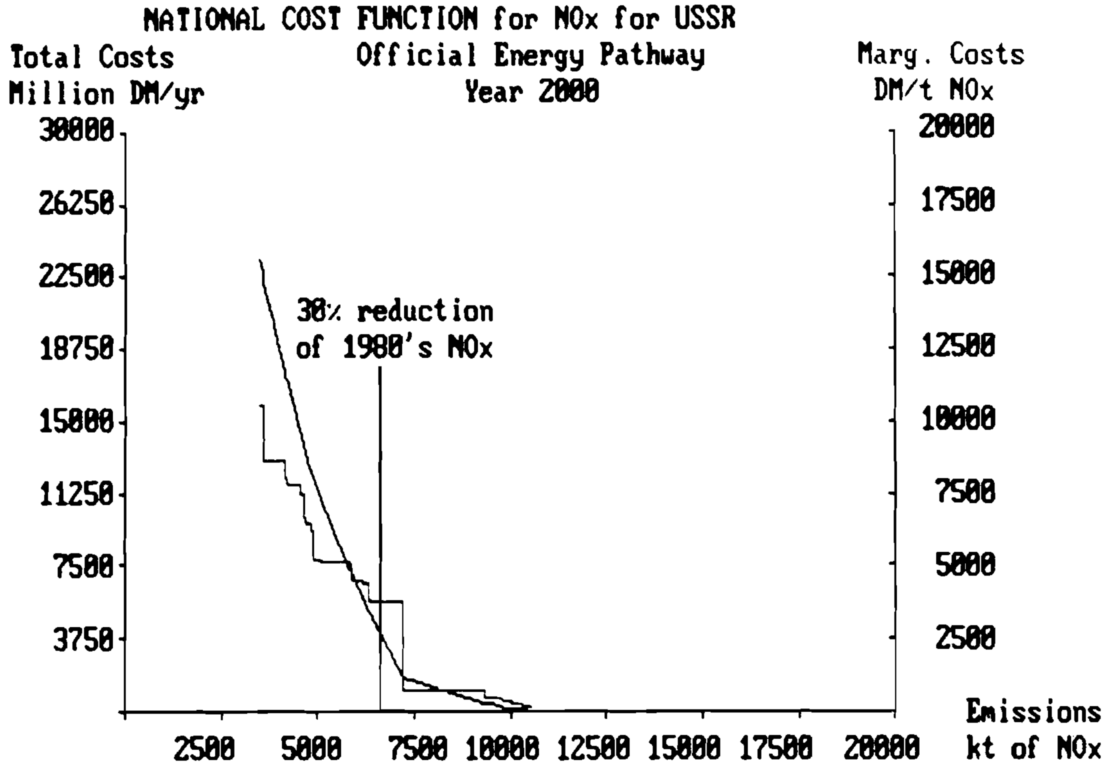



NATIONAL COST FUNCTION for NOx for Sweden
Official Energy Pathway
Year 2000
Total Costs
Million DM/yr
Marg. Costs
DM/t NOx
800
700
600
500
400
300
200
100
20000
17500
15000
12500
10000
7500
5000
2500
30% reduction
of 1980's NOx
50
100
150
200
250
300
350
400
Emissions
kt of NOx


NATIONAL COST FUNCTION for NOx for Switzerland
Official Energy Pathway
Year 2000
Total Costs
Million DM/yr
Marg. Costs
DM/t NOx
400
350
300
250
200
150
100
50
20000
17500
15000
12500
10000
7500
5000
2500
30% reduction
of 1980's NOx
50
100
150
200
250
300
350
400
Emissions
kt of NOx

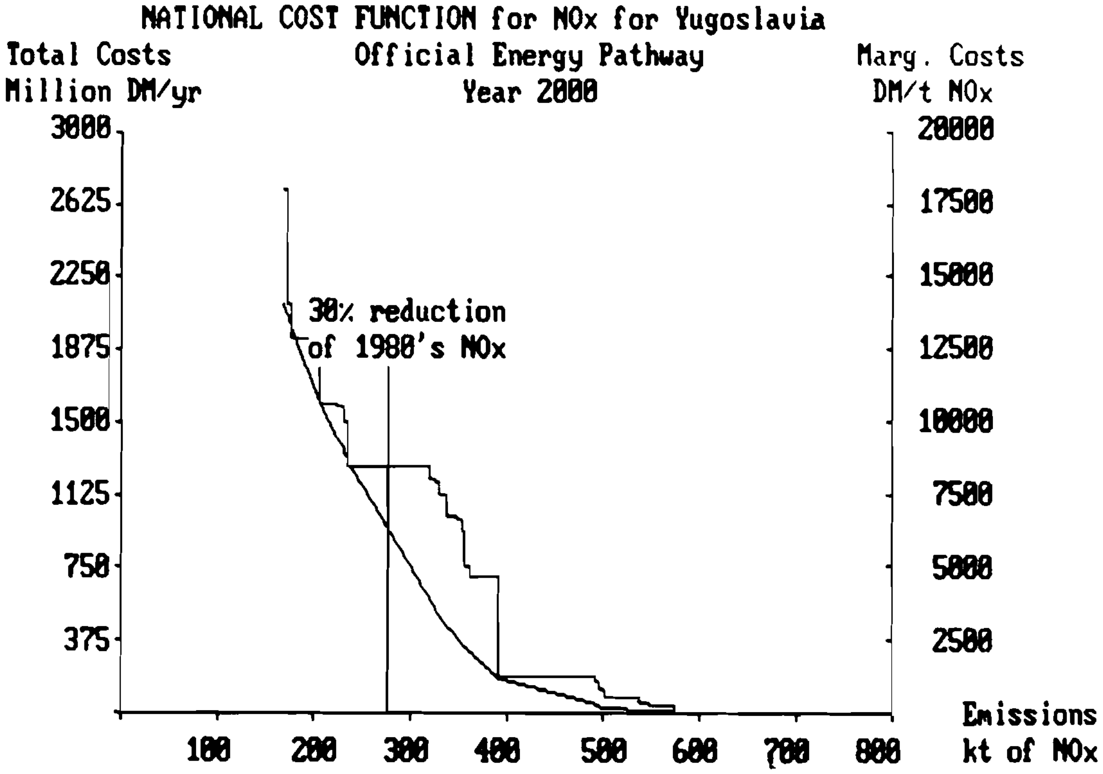

NATIONAL COST FUNCTION for NOx for Turkey
Official Energy Pathway
Year 2000
Total Costs
Million DM/yr
Marg. Costs
DM/t NOx
3000
2625
2250
1875
1500
1125
750
375
20000
17500
15000
12500
10000
7500
5000
2500
30% reduction
of 1980's NOx
250
500
750
1000
1250
1500
1750
2000
Emissions
kt of NOx


NATIONAL COST FUNCTION for NOx for United King.
Official Energy Pathway
Year 2000
Total Costs
Million DM/yr
Marg. Costs
DM/t NOx
6000
5250
4500
3750
3000
2250
1500
750
20000
17500
15000
12500
10000
7500
5000
2500
30% reduction
of 1980's NOx
375
750
1125
1500
1875
2250
2625
3000
Emissions
kt of NOx


NATIONAL COST FUNCTION for NOx for USSR

Official Energy Pathway

Year 2000


NATIONAL COST FUNCTION for NOx for Yugoslavia

Official Energy Pathway

Year 2000