Evaluating the direct costs of controlling NOx emissions in Europe

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1996

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ABSTRACT

This study summarises the available information on the costs of those nitrogen oxides abatement technologies in operation at present or coming into operation in the near future. Relying on disaggregated source data and using engineering cost functions and various technical and economic assumptions, the least cost curves of nitrogen oxides abatement for all the European countries have been derived and some examples are presented.

JEL Classification code: Q2

Keywords: Denitrification; abatement costs.

INTRODUCTION

The generation of electricity from conventional power stations is associated with a number of environmental problems. For example, generation using coal causes significant air pollution due to emissions of sulphur oxides, carbon dioxide, nitrogen oxides and particulates. In the UK a 2000 MW coal fired station operating at 60% load factor bums about 4 .4 million tonnes of coal per year and each year emits into the atmosphere about 10 million tonnes of carbon dioxide, 130,000 tonnes of sulphur dioxide, 40,000 tonnes of nitrogen oxides and between 4,000 and 40,000 tonnes of particulate matter depending on how well the stack emissions are cleared before they are released (Highton and Webb, 1980). Most of the attention about the detrimental effects of acidification has been given to sulphur emissions. But emissions of nitrogen are also important in contributing to acidification and to other environmental problems. The results reported here differ from any previously reported as new abatement costs are derived from detailed plant-level research. The paper also provides a concise review of the literature on nitrogen oxides control as well as the economic and technical assumptions on which these costs rely on.

Nitrogen oxides and ammonia are the greatest part of nitrogen emitted by anthropogenic activities. They contribute almost 40% of the acidification problem and their sources are power stations, industry and vehicles. They take the form of nitric oxide, and nitrogen dioxide and a small proportion of nitrous oxide. Ammonia emissions originate from animal wastes, fertilizers and industries. Livestock wastes are estimated to account for approximately 80% of total European emissions. However, since the cost estimates for controlling ammonia emissions are more uncertain than those for controlling nitrogen oxides due to limited practical experience, the analysis here will be limited to nitrogen oxides as the polluting substance to control.

Nitrogen oxides are formed by either oxidation of the nitrogen contained in the fuel (fuel NO_x) or by the high-temperature combination of oxygen and nitrogen in the combustion

air (thermal NO_x). The fuel NO_x emissions are a function of the fuel and the firing mode used. Thermal NO_x emissions are a function of the combustion temperature, residence time and stoichiometry. When coal and heavy fuel oil are burnt below temperatures of 1400 ° C fuel NO_x dominates, while for higher combustion temperatures and for other fuels thermal NO_x is more important (Amann, 1989). The biggest proportion of nitrogen oxides is emitted as monoxide and is oxidized in the atmosphere to NO_2. The latter contributes to the global warming effect.

In this study, section 1 describes the technical characteristics of the available nitrogen oxides control techniques and presents the cost estimates used in this study for the derivation of the European abatement cost curves. Section 2 details the economic and technical assumptions used in the derivation of the abatement cost curves. Section 3 discusses the empirical results and finally, some concluding remarks are presented.

1. ABATEMENT OPTIONS FOR NITROGEN OXIDES EMISSIONS REDUCTION

Estimates of the costs of pollution control systems provide a common language for making international comparisons. Denitrification techniques exist to reduce the nitrogen content of the fuel in use. The extent of removal is dependent on the physical and chemical characteristics of the nitrogen in the fuel. For power plants and industrial boilers abatement techniques may be applied before, during and after combustion. Before combustion it is possible to have both fuel switching and reductions in the consumption of fuels that lead to high NO_x emissions. The cost effectiveness of fuel switching depends on relative prices of fuels and nitrogen content and the removal efficiency is expected to be as high as 70%. It can be utilised by all users.

During combustion we can control NO_x with combustion modification techniques. Improvements in boiler design may result in significant reductions of NO_x emissions. The level of emissions depends on the type of the plant and, specifically, on the fuel-to-air ratio and the spacing of the burners. Combustion modifications try to reduce the excess oxygen

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levels and the peak flame temperature. Primary modifications may be applied to new and existing plants and also used in combination with secondary flue gas treatment. The main types of abatement systems currently in operation are the following:

Low NO$_x$ burners (LNB) rely on the reduction of both thermal and fuel NO$_x$ formation by adjusting the flame in the combustion process. It is easy to install and causes very limited energy loss. The abatement efficiency is expected to be approximately 30%. Its operating costs are negligible while its capital cost is approximately $4 million in the context of a new 500 MW$_C$ coal-fired power station operating with a 70% load factor. The capital cost is a function of the construction cost (which varies by country), the retrofit factor (installation on a new or existing plant), the fuel type and plant capacity. This technique's cost effectiveness ranges between $7-$26 per tonne of NO$_x$ removed.

Off-stoichiometric combustion achieves reductions up to 30%. Most of the applications have been in coal-fired units. It reduces the formation of fuel NO$_x$ and some of the thermal NO$_x$ by regulating the oxygen content in the furnace.

Catalytic combustion uses a catalyst to achieve oxidation of fuel rather than high temperature. Fuel and air are mixed and enter a chamber containing the catalyst. This results in the creation of nitrogen and other gases. It can be used in thermoelectric power plants, industrial boilers and process heaters including petroleum refineries. At present, it is not commercially available and it is not considered in our analysis due to the lack of practical experience.

Fluidized Bed Combustion (FBC) is a combustion process in which coal or other fuel and process air are injected into a bed made up of particles of inert mineral pattern as ash, sand or limestone. Combustion takes place in a turbulent mixing of the particles created by the gas flow through the bed. NO$_x$ emissions are reduced by up to 80% compared to conventional boilers of the low operating temperature variety. It is applicable to new solid fuel fired industrial and utility boilers, although due to lack of empirical evidence, its cost-effectiveness is undefined. Halkos (1995) provides the capital the fixed and variable operating and

maintenance costs and the cost-effectiveness of an FBC unit for sulphur abatement. It is worth mentioning that this is the only technology that can be applied for joint abatement of sulphur and nitrogen oxides.

Finally, after combustion flue gas cleaning devices can be employed. Depending on the use of catalysts we can distinguish the following two types of flue gas denitrification:

a. The selective catalytic reduction (SCR) uses ammonia to convert nitrogen oxides into nitrogen and water in the presence of a catalyst. Ammonia is injected at a stoichiometry ratio to nitrogen monoxide in the flue gas of 0.9:1. It does not produce a by-product. Its abatement efficiency is approximately 80% and depends on how quickly the exhaust gas stream moves through the catalyst and on the amount of ammonia added. The annualized capital cost for the catalyst depends on the catalyst volume, the plant capacity, the catalyst price and the capital recovery factor. The following table presents on the left the capital requirements and on the right the fixed costs (in million 1985 $) of a SCR for a larger than 100 MW_C coal-fired power station (Laikin et al, 1991).

Capital requirements of an SCR		Fixed costs of an SCR	
Catalysts	9.21	Insurance and taxes	0.63
Ammonia storage	1.09	Maintenance and repair	0.95
Construction	1.19	Catalyst replacement	3.60
Buildings, land	3.19		
Equipment	13.21		
Interest/contingency	3.84		

SCR is more expensive than low NO_x burners and the OECD (1983) estimates capital costs of an SCR at $15-60/kW of plant capacity depending on boiler size and the inclusion of heat recovery systems. The fixed operating and maintenance (O and M) costs consist of labour and of administration and maintenance (5% of total capital cost excluding catalyst). The variable O and M costs depend on the use of ammonia and electricity. We assume a stoichiometry ratio (NH_3: NO_x) of 0.9 : 1, equivalent to 0.33 tonne NH_3 per tonne NO_x at inlet; the cost of ammonia is assumed to be $200 per tonne of NH_3. The cost of electricity is assumed to be equal to $50 per MWh multiplied by the specific electricity price scale for

differences between countries (Scharer et al., 1987; Leggett, 1986; UNECE, 1986; Scharer and Haug, 1986). Amann (1989) claims that the costs for electricity production at new power plants burning brown coal may vary between $0.24 and $O.33 /kWh and from $0.19 to $0.28/kWh for plants burning hard coal. Amann relates these costs to the amount of NO_x removed and costs range from $0.96 to $1.31 /kg NO_x for brown coal and from $0.7 to $1.04 /kg NO_x for hard coal. Differences are due to capacity utilization and boiler size distribution.

The capital recovery factor for the catalyst investment can be estimated by dividing the catalyst life (in years) by the plant operating time (hours/year) and where we assume a discount rate of 5% and 3 years of economic life. The last assumption is due to the fact that after some time of operation, the activity of the catalyst declines and it thus has to be changed periodically. The activity of the catalyst decreases by almost 15% per 8000 hours operation. For catalyst replacement a capital recovery factor of approximately 40% per year is assumed. The following table provides information on the catalyst volume used in power plants and in industry (Scharer et al., 1987; Leggett, 1986; UNECE, 1986; Scharer and Haug, 1986).

Fuel type	Catalyst volume (m^3/MW_e)		Price ($/m^3$)	Life (hours)
	Power plants	Industry		
Hard coal/lignite	1.3	0.43	10000	15000
Oil	0.65	0.22	10000	25000
Gas	0.33	0.11	10000	35000

The cost effectiveness of this technology ranges from $820-$1850 per tonne of NO_x removed with a capital cost equal to $26.5 million in the case of a new 500 MW_e coal-fired power station operating with a 70% load factor and operating cost equal to approximately $0.2 /kWh.

b. The selective non-catalytic reduction: This technique abates NO_x by direct injection of ammonia into the combustion zone, but since no catalysts are required, this lowers the initial costs and the extra costs for catalyst replacement. It is also temperature sensitive and its effectiveness is between 50% and 70% depending on the level of ammonia input and on successful temperature control. It produces ammonium sulphate as a by-product and it can

release ammonia. The ammonia use depends on the abatement efficiency assumed. If we assume a 50% removal efficiency then the stoichiometry ratio ($NH_3 : NO_x$) is 2 : 1, equivalent to 0.73 tonne NH_3 per tonne NO_x at inlet. If we assume abatement efficiency equal to 70% then the stoichiometry ratio becomes 3 : 1, equivalent to 1.1 tonnes NH_3 per tonne NO_x at inlet. In both cases the assumed cost is $200 per tonne NH_3 (UNECE, 1986; Leggett, 1986; OECD, 1983; Dacey, 1984). Its operating costs are negligible, while its capital cost is approximately $10 million for a new 500 MW_e coal-fired power station operating with a 70% load factor and its cost-effectiveness ranges between $680- $1420 per tonne of NO_x removed.

For mobile sources we must distinguish between diesel and gasoline powered vehicles. As there is no catalyst technology commercially available to reduce NO_x emissions from diesel engines, emissions must be reduced by modifying the engine design and improving the combustion process. For passenger cars, buses and trucks we can use engine modifications (such as the use of uncontrolled catalytic converters or lean-burn engines) and exhaust gas recirculation (EGR). EGR reduces NO_x emissions by lowering the peak combustion temperature. This is done by returning to the combustion chamber a proportion of the exhaust gas and in this way replacing some of the air. Abatement efficiency may be up to 30% without any increase in fuel consumption. Cadman and Johnson (1986) claim that EGR increases wear rates and oil contamination which imply higher maintenance expenses and also shorter engine lifetime.

Installation of oxidation catalysts is possible to achieve lower hydrocarbons and carbon monoxide emissions compared with engine midifications alone, but requires the use of unleaded fuel to avoid poisoning the catalyst. In Europe the lean-burn engine concept, goes beyond traditional engine modification measures to reduce NOx and HC. NO_x emissions are reduced by changing stoichiometry of the fuel-to-air ratio to leaner mixtures. It is designed for new vehicles and requires some changes in the design of engines. But at high speed and because of the high oxygen of the exhaust gas its emissions may be more than those of cars without control (Amann, 1989). Lawson (1986) claims that the cost- effectiveness of NOx

abatement (in 1985 $/tonne) ranges between 100 and 700 for stationary sources and 140 and 850 for mobile sources. At the same time HC cost effectiveness ranges from 240 to 650 for stationary sources and 70 to 500 for mobile sources. Lawson concludes that hydrocarbon reductions from mobile sources are more cost-effective than comparable reductions from stationary sources, while mobile source NOx reductions may be less cost effective. The costs for stationary sources are attributed to US EPA estimates. Searles (1986) claims that an oxidation catalyst results in incremental costs of about $200-$400 compared to the lean-burn engine without the catalyst. A fuel penalty of about 6% would also be incurred with the catalyst. Fuel penalty ($/vehicle/year) is a function of utilization (km/vehicle/year), fuel-efficiency (litre/km) and fuel price ($/litre). Fuel penalty costs are calculated assuming here a pretax fuel price equal to $0.25 per litre and that new vehicle efficiency improves by 1% per year from 1980 to 2000.

For gasoline cars, a very promising technology to reduce NOx emissions is a special three-way catalytic converter. It is fitted to the vehicle exhaust and contains beads and a combination of the precious metals platinum (85%) and rhodium (15%) (McCormick, 1989). Each converter needs about two grammes of precious metal. In this method, the proportions of nitric oxide, carbon monoxide and hydrocarbons enter the catalytic converter. The gases from the engine pass through the converter which oxidizes carbon monoxide and hydrocarbons to carbon dioxide and water and reduces NO_x to nitrogen. The ratio of air and fuel in the combustion chamber is regulated. Too much oxygen results in increased NOx emissions and too much fuel in increased carbon monoxide and hydrocarbons.

This method cannot however be used with diesel engines. The three-way converter is complex and requires precise monitoring and careful control of the air/fuel mix in the combustion chamber. It is also expensive; McCormick (1989) cites an average annual cost of about $60 to $80 per car including purchase of converter and maintenance over 10 years. It is also sensitive to lead and this makes it useless in countries that rely on leaded petrol. If no credit is given for simultaneous reduction of VOC and CO then the three-way catalyst is one

of the most expensive options for controlling NO_x and costs may vary between $1.27 and $3.6 /kg NO_x. If NO_x, VOC and CO are weighted equally then the range is between $0.16 and $0.45 /kg of abated pollutant (Amann, 1989).

We can also use uncontrolled catalysts which do not control the fuel-to-air ratio. The catalyst reduces CO and VOCs. Its efficiency is lower compared with controlled three-way catalysts. The following table presents some of the available options for controlling NO_x emissions from mobile sources. Emission controls are available only for new vehicles. There is no control method modelled for motorcycles and 2-stroke cars. Unleaded gasoline is assumed to be widely available and costs of conversion to unleaded and changes in vehicle running costs are not considered. Also operating and maintenance costs due to adoption of emission controls such as altered servicing costs are not included.

Option	Capital Cost ($/vehicle)	NO_x abatement (%)	Fuel penalty (%)
1.Gasoline automobiles	and light trucks	(<3 tonnes)	
EGR	100	20-50	1.5-6.0
Uncontrolled catalyst	350	50	5.0
Controlled catalyst	500	80	5.0
Catalyst and EGR	600	90	5.0
2. Diesel automobiles	and light trucks	(< 3 tonnes)	
EGR and other engine modifications	200	20-50	1.5-6.0
3. Heavy trucks/ buses			
EGR and other engine modifications	500	20-50	1.5-6.0

Sources: NAPAP (1987); Leggett (1986); Walsh (1987); OECD (1986, 1988); Searles (1986)

Table 1 presents the factors leading to differences between countries. These factors are the annual energy consumption per vehicle and the fuel prices for the additional energy use. The fleet composition and the typical driving cycles are important determinants of the average emissions factors but it is not feasible to collect such detailed data. It is worth mentioning that

increased speeds and higher volumes of traffic will lead to upward revision in our estimates of NOx emissions from cars. The reduction in speed limits will lead to reductions in NOx and CO2 emissions. Fergusson (1994) claims that NOx emissions may be reduced by 4% if we enforce speed limits of 70 miles per hour (mph), by 7% if we enforce 60 mph and by almost 12% if we reduce speed limits to 50 mph. At the same time the savings in carbon dioxide will be 3.1%, 5.2% and 7% respectively.

2. ASSUMPTIONS USED IN THE DERIVATION OF THE ABATEMENT COST CURVES

The costs used in this study relate to the direct cost of construction, operation and design of nitrogen oxides abatement units. A full economic analysis would require also the inclusion of financial factors such as interest payments, subsidies and taxes, and an examination of the external costs imposed by the operation of the control unit (for example, waste disposal, etc). Given the generic engineering capital and operating control cost functions for each efficient abatement technology, total and marginal costs of different levels of emission reduction for each individual source (power plant, industrial boiler, petroleum refinery, vehicles) at the national (country) level can be constructed. The previous section summarized the available information on the technical characteristics and costs of those abatement technologies in operation at present to reduce the nitrogen content of fuels in use. We have seen that abatement technologies differ both as to cost and applicability (depending on the physical and chemical characteristics of the fuel used and on the size of abatement plant). It is assumed that control costs are independent of order of introduction and that abatement technologies are scale specific. Each abatement technology is efficient over a defined range of nitrogen removed; we have constant returns to scale over the range of abatement at which each technology is potentially efficient. In other words, each technology reduces emissions by some proportion, called the "abatement efficiency", which is assumed to be fixed for each control method at the plant size at which the method is efficient. For

example, a SCR unit has an abatement efficiency of 80% at the efficient plant size. Also, fuel use and costs are assumed to be independent from abatement policy. For the purposes of this exercise then, abatement by means of reducing the output of electricity or other industrial output is ruled out[1]. Finally, another basic assumption of the cost module is that there is a competitive market for NO_x abatement technologies accessible to all European countries.

It is assumed that the regulatory authority seeks to maximize abatement subject to a budget constraint. It would be economically inefficient to introduce relatively costly control options unless opportunities for using cheaper alternatives had already been exhausted. The economic efficiency of alternative abatement options (expressed as $ per tonne pollutant removed) depends on site specific conditions. The set of source-specific emission reduction opportunities can be merged in order of increasing marginal cost to yield a least cost emission reduction function for each country[2]. Marginal cost increases are due to the effect of switching between technologies as the scale or level of abatement rises. The corresponding point on the marginal cost curve specifies the set of country control options which minimize total abatement costs (Halkos, 1992, 1994; Mäler, 1990). The marginal cost curve is a discontinuous step function with each step representing a particular discrete abatement technology. The level of each step indicates the incremental cost of a technology relative to the maximum incremental amount of NO_x removed by introducing that technology. The sequence of efficient technologies gives us the long run marginal cost of abatement. At the low end of the curve the least expensive strategies are presented; the greater the percentage of pollutant removed, the higher will be the cost of removing an additional amount.

The actual control costs of each abatement technology are defined by national circumstances and the abatement cost curves depend on the energy scenario adopted[3]. Such abatement costs differ considerably among countries even for the same technology and these cost estimates take into account a wide range of site and plant specific factors, e.g. plant size, fuel type, initial nitrogen content of fuel, load factor and new or retrofit application (remaining life).

Table 1: European fuel prices (without taxes) and energy consumption per vehicle.

Countries	Gasoline Fuel price ($/MJ)	Diesel Fuel price ($/MJ)	Gasoline consumption GJ/car/year	Diesel consumption GJ/car/year
Albania	3.7	4.365	45	400
Austria	4.365	4.752	49	790
Belgium	3.3	4.205	45	650
Bulgaria	3.7	4.365	81	400
Former CSFR	3.7	4.365	30	310
Denmark	4 .01	3.95	44	520
Finland	4.58	6.508	44	780
France	3.17	3.183	35	840
FRG	2.98	3.67	47	640
Former GDR	3.7	4.365	41	150
Greece	2.4	3.03	62	390
Hungary	3.7	4.365	49	320
Ireland	4.5	4.43	65	600
Italy	3.36	4.01	31	600
Luxembourg	3.22	4.161	49	810
Netherlands	3.4	4.226	43	910
Norway	3.9	4.5	45	280
Poland	3.7	4.365	35	260
Portugal	3.9	4.62	28	840
Romania	3.7	4.365	45	400
Spain	3.4	3.8	33	490
Sweden	4.64	4.71	55	630
Switzerland	3.72	4.13	52	260
Turkey	4.5	6.97	45	400
UK	3.63	3.74	54	440
Former USSR	3.7	4.365	58	510
Yugoslavia	3.7	4.365	31	380

Source: Amann(1989)

The economic life of emission sources varies between the different types of sources. It is assumed here that abatement costs are annualized over 30 years at new power plants, 20 years at new industrial boilers and for mobile sources, over tire average life of each type of vehicle in each individual country. The lifetime of catalysts for gasoline vehicles is assumed to be 10 years. For retrofits to existing power plants, we assume default lifetimes of 15 years for power stations and 10 years for industrial boilers, unless other information is available about the plant s commissioning date.

The nitrogen contents range between 0.5% and 2% in hard coal, from 0.3% to 1.2% in heavy fuel oil, and it is less than 0.1% in oil distillates. Natural gas does not contain nitrogen (Amann, 1989). It is recognized that it is more expensive to retrofit an abatement technology to an existing plant than it is to design it into a new plant. Retrofit of equipment systems is usually assumed to carry a cost penalty of 10% to 40% over the cost of installation with new plants. Here, an average approximation of 25% higher capital cost than the equivalent at a new plant is used.

Country specific capital and operating cost adjustment factors have been estimated to take into consideration differences between countries in electricity, labour and construction costs. Electricity costs arise as many abatement technologies consume electricity in their operation. An indicator of the costs of electricity is assumed to be the average pre-tax price industrial consumers are required to pay for electricity in each country. Average prices were estimated in US $ for each country from IEA (1986) and national statistical sources and normalized against the FRG[4] to obtain the index presented in table 3. Labour is employed in the operation and maintenance of emissions control plant but also in the construction and design of plant. For each country, average hourly earnings in the manufacturing sector in US $ were estimated (ILO, 1986) and normalized against the FRG once more to obtain an index. Finally, the investment costs of abatement measures may vary between countries due to differences in the cost of construction materials, labour costs and labour productivity. We have assumed that relative costs are only influenced by labour. In order to develop a crude

construction cost index, based on the approach sketched in ICE A/ACE (1988), it is assumed that in the FRG labour represented 30% of the total construction cost of an SCR plant and materials 70%.

The cost of an emission abatement method is given by the total annualized cost (TAC) of an abatement option, including capital and operating cost components:

$$TAC = [(TCC) * (r / (1 - (1+r)^{-n})] + VOMC + FOMC$$

where TCC is the total capital cost ($), VOMC and FOMC are the variable and fixed operating and maintenance costs ($) respectively and $(r / (1 - (1+r)^{-n})$ is the capital recovery factor at real discount rate r, which converts a capital cost to an equivalent stream of equal annual future payments, considering the time value of money (represented by the discount rate, r); n represents the economic life of asset (in years). The estimation of the annual operating and maintenance costs requires a great deal of infonnation (for example, the nitrogen content of fuel used, the annual operating hours, removal efficiencies of the control methods, etc) and consists of a fixed portion that is dependent on the use of the plant (e.g. maintenance and labour costs) and a variable portion dependent on the prices for electricity, labour, sorbents and waste disposal and the specific demand for energy due to the abatement process. Table 3 presents the applicability requirements, the abatement efficiencies and the capital and operating costs of the main abatement options, as well as an estimate of the cost-effectiveness for each abatement technology.

Table 2: Electricity, labour and construction cost factors.

Countries	Labour (FRG=1.00)	Construction (FRG=1.00)	Electricity (FRG=1.00)
Albania	0.10	0.73	0.50
Austria	0.96	0.99	0.90
Belgium	0.90	0.97	0.90
Bulgaria	0.23	0.77	0.50
Czechoslovakia	0.42	0.83	0.50
Denmark	1.30	1.09	0.95
Finland	0.95	0.99	0.90
France	0.80	0.94	0.70
FRG	1.00	1.00	1.00
GDR	0.30	0.79	0.50
Greece	0.41	0.82	0.70
Hungary	0.11	0.73	0.50
Ireland	0.81	0.94	1.30
Italy	0.90	0.97	1.05
Luxembourg	1.00	1.00	0.85
Netherlands	1.05	1.02	1.00
Norway	1.30	1.09	0.20
Poland	0.14	0.74	0.35
Portugal	0.20	0.76	0.80
Romania	0.17	0.75	0.50
Spain	0.60	0.88	0.75
Sweden	1.24	1.07	0.50
Switzerland	1.20	1.06	1.00
Turkey	0.10	0.73	0.70
UK	0.86	0.96	1.00
USSR	0.30	0.79	0.40
Yugoslavia	0.15	0.74	0.55

Table 3: Nitrogen oxides emission abatement options and costs (costs in $ million 1985). Costs for stationary sources are based on a new 500 MW power plant, using hard coal of 1% nitrogen content, 70% load factor. For mobile sources costs are for average European automobile of 1200 kg.

Abatement Method	Applicability	NOx removal efficiency (%)	Capital Cost	Operating and Maintenance cost	Cost- effectiveness $/t NO$_x$ removed
Fuel switching (e.g. oil to gas)	All users	Up to 70	-	-	Depends on relative price and nitrogen content
Low NO$_x$ Burners	Power plants and industrial boilers	30	$3.9 m	Negligible[1]	7-26
Combustion modifications	Power plants and industrial boilers	35	$6.5 m-$18.9m	Negligible[1]	6-70
Flue Gas Denitrification SCR SNCR	Power plants and industrial boilers	80 50-70	$26.5 m[1] $10.1 m	$0.2 /kWh Negligible	820-1850 680-1420
Fluidized Bed Combustion (FBC)	Power plants and industrial boilers	80	-	-	Undefined
Exhaust Gas Recirculation	Automobiles	Up to 30	$45-$84	Fuel efficiency change -5% to +0%	0-4500
Lean Burn Engines	Automobiles	80	$210	Fuel efficiency Change -5% to +15%	Savings of 5-85 per vehicle
Exhaust catalysts	Automobiles	90	$170-$520	Fuel efficiency change -4% to +5%	1300-1700

(1) We have assumed there are no incremental operating costs associated with these modifications.

(2) Excluding catalyst's costs.
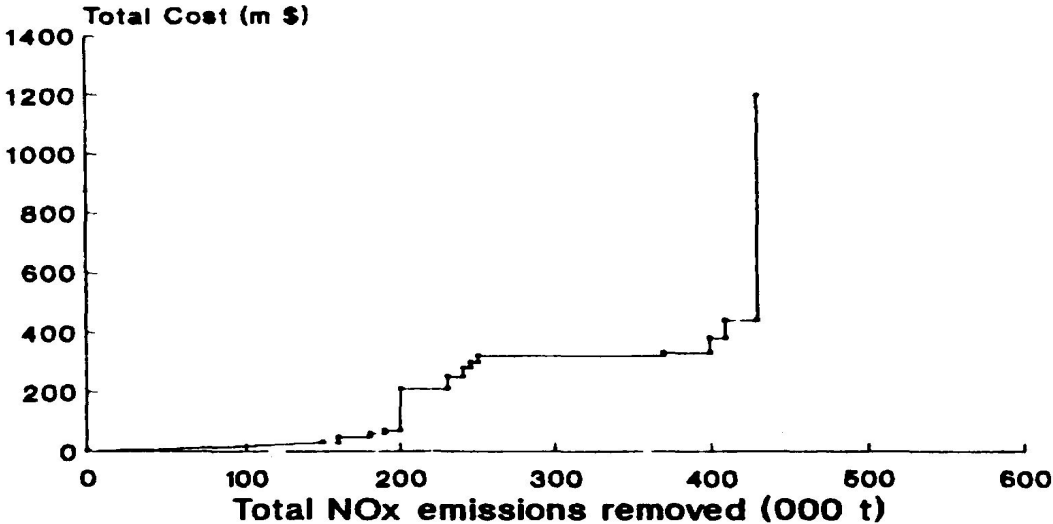
3. EMPIRICAL RESULTS

In order to compare the abatement costs between countries, the least cost combination of abatement options for each emission reduction level from zero reduction up to the technical feasible limit is derived. Cost estimates for each technology are influenced by fuel type, plant size, nitrogen content of fuel, new or retrofit application and labour, construction and electricity cost factors. The slopes of the total abatement cost curves differ from country to country and if the slope of the total abatement cost curve for one country is steeper than for another, for any given abatement level, then the abatement cost in the first country is higher than in the second. Given projections of uncontrolled emissions, estimates can be made of the potential for their reduction using available abatement technologies and of the likely cost. Following the assumptions mentioned in section 2, total and marginal abatement cost curves can be derived for each European country. Figures 1 and 2 present the total abatement cost curves for Greece and the UK. The potential of the abatement technologies for reducing emissions in a particular country depends on the existing pattern of energy use. Table 4 presents the unconstrained emissions in the year 2000[5]. the maximum Feasible national emission abatement levels through the use of all available technologies and combination of technologies and the associated cost of achieving this maximum abatement in each country, as well as the total costs of achieving a 30% nitrogen oxides emissions reduction.

Thus, it can be seen that, for example in Greece, a 30% NO_x emissions reduction costs $14.5 million, while a 50% reduction (the maximum that can be achieved in Greece) requires an amount of $356 million, which shows how much more expensive is the reduction of the extra twenty percent when a certain level of abatement is reached. Similarly, for Spain a 30% reduction requires $87 million, while a 47% reduction requires $1,179 million and, for Belgium, a 30% reduction costs $34 million and a 56% reduction costs $332 million and so on.

Similarly, the total cost of a uniform 30% reduction varies from $4 million in Ireland to $710 million in the former USSR. The UK has a total cost of $396 million at this

percentage level while the FRG has a total cost of $174 million, Austria of $21 million and Norway of $52 million. Similarly, we can find the total costs for all the European countries and for the two different percentages (30% and maximum feasible abatement). The final interesting conclusion of Table 4 is that the total cost for all European countries of achieving different percentage reductions increases drastically in all cases as the reduction is moved from 30% to the maximum feasible abatement. A 30% reduction requires a cost of $1,750 million while the maximum feasible abatement costs $24,386 million.

FIGURE 1
GREECE (YEAR 2000)

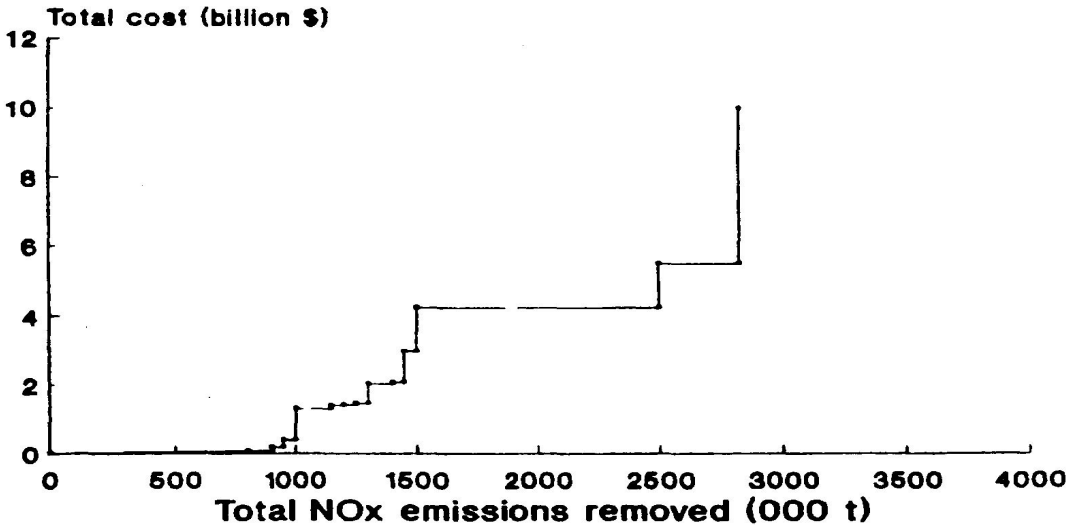
Figure 2
UK (YEAR 2000)

Table 4: Total cost of a 30% and of maximum emissions reduction

Countries	Unconstrained emissions Year 2000	Maximum emission reductions (%)		Total costs (in million $ 1985)	
				Maximum reduction	30% reduction
Albania	37	48		52.99	17.3
Austria	181	51		140.29	21. 06
Belgium	307	56		331.52	34. 31
Bulgaria	440	51		486.41	58.76
Former CSFR	293	69		524.12	29.3
Denmark	129	56		168.82	20.04
Finland	247	57		285.67	98.17
France	1021	71		1012.57	172.55
FRG	1422	66		1822.35	173.57
Former GDR	360	78		1181.39	35.6
Greece	293	50		355.98	14.53
Hungary	239	49		267.32	18.9
Ireland	64	53		54.69	3.8
Italy	1233	64		1391.64	514.27
Luxembourg	33	53		17.32	5.43
Netherlands	382	67		457.54	52.31
Norway	178	46		148.10	51.63
Poland	848	71		1507.47	72.36
Portugal	220	43		219.77	29.33
Romania	670	54		830.84	69.45
Spain	1223	47		1179.0	87.27
Sweden	245	59		204.48	30.23
Switzerland	91	64		82.88	14.95
Turkey	1168	47		899.80	232.44
UK	1309	68		1971.13	395.88
Former USSR	6037	63		8164.40	709.51
Yugoslavia	347	51		627.38	107.81
Total/Average	19017	57.5		24386	1750

CONCLUDING REMARKS

Currently available technologies for NO_x have been classified into three categories: pre-combustion, during combustion and post combustion. Combustion modifications and low NO_x burners at power plants and exhaust gas recirculation and lean burn engines for mobile sources are relatively cost-effective. But best available technologies for power plants, petroleum refineries and industrial boilers seem to be a combination of combustion modification and selective catalytic reduction achieving a 90% reduction. At the same time and for gasoline cars, the three-way catalytic converter seems to be the most cost-effective method, achieving an 80% reduction. Fuel switching can be shown to constitute a good solution to the problem, but its cost-effectiveness depends on the relative prices and the nitrogen contents of the fuels used. Fluidized bed combustion (FBC) is the only technique that can be used simultaneously for nitrogen oxides and sulphur abatement, but it can only be used for new installations, and would only have an effect on total emissions over a long period. It is not possible to define abatement costs precisely since air pollution control is an integral part of the FBC boiler design. Low NO_x burners and combustion modifications could have low operating and maintenance cost, but they can be used in cases where only moderate NO_x emission reductions are required. The SCR is the only technique available for achieving very high removal efficiency at all types of installation, new or retrofit. SCR dominates the market in Europe having achieved a first mover advantage and thus it is difficult for other (probably better) control methods to compete against it. As mentioned it can be used in combination with combustion modifications to achieve a reduction of 90%. The general trend is for low NO_x burners to have the lowest capital costs, with combustion modifications and SCR technologies having the highest costs. It is worth mentioning that if methods like catalytic combustion become available, then their performance will be better than those of conventional methods and this leads us to conclude that we may overestimate future control costs.

Finally, in order to minimize the costs for a given reduction of NO_x emissions, the different denitrification technologies can be used in the least-cost combination. It was shown that the greater the percentage of pollutant already removed, the higher the cost of removing an additional amount. Initially, those sources of pollution are eliminated that can be removed most cheaply and easily. Further reductions in pollution will usually prove more than proportionately costly and difficult. This means that there is a maximum marginal quantity of nitrogen oxides removed and that, after this point the pool of technologies starts to be less efficient, i.e. the marginal quantity of NO_x removed decreases progressively. This implies the rise in marginal costs which is evident from the curves. The important point is how steeply marginal cost rises with each successive increase in pollution control objectives. Obviously, there exist countries where abatement is cheaper. As the transboundary nature of the acid rain problem requires cooperation between countries in order to achieve environmental targets, this implies that an international optimization with co-ordination of side payments must be carried out (for more details see Halkos, 1993, 1994).

ENDNOTES

[1] Other types of abatement options that are omitted in this approach are abatement through energy conservation in its broadest sense (energy demand suppression, fuel switching and efficiency measures) and fuel substitution.

[2] Twelve individual fossil fuel types consumed by 5 economic sectors have been taken under consideration The fuel types include hard coal and derivatives, coke, brown coal and derivatives, other primary solid fuels such as peat and wood, heavy oil products (refinery fuel oil and residual fuel oil), gasoline, diesel and middle distillates (gas oil and diesel oil) in which the available abatement technologies are applied and natural gas. The economic sectors identified include thermo-electric plants (including district heating), industry (split between iron and steel, process emissions and others), the energy sector (split between refineries and others), transportation and other sectors (including residential, commercial and agriculture). For this reason a program in Basic has been constructed by the author. The program consists of five separate algorithms, each corresponding to a single sector. The results of all algorithms are merged in a unique output file.

[3] If emission factors are assumed to be essentially invariant over time, then changes in potential emissions in the absence of abatement are wholly determined by changes in total energy consumption and the fuel mix. Data on annual energy consumption by fuel type and demand sector are available in matrices known as 'energy balances'. The main sources considered by the author regarding energy balances for the year 2000 are IEA (1991) for Western European countries and UNECE (1991) for Eastern European countries. Key sources of data include ICEAR (1986), Pennwell Directories (1986), Petroleum Times (1986) and SPRU (1986). Using these data, a database of the existing stock of power stations, petroleum refineries and large process emission sources (pulp and paper mills, primary smelters and iron and steel works) in each country has been created and consists of records for almost 1000 individual power stations, 250 petroleum refineries and 200 process emission sources.

[4] The data on which these estimates are based are projections made prior to the unification of Germany. For this reason the report refers to the Federal Republic of Germany, not Germany. It turns out however; it is useful to work with the 'old data'. It does not make much sense to aggregate FGR and GDR simply for the sake of using current boundaries for the reason that historic policies in the two areas have been so different.

$$NR_p = AE_t * MW_p * [\, (N_{if} * R_f * D_{ijf}) \, / \, MW_{iijf} \,]$$

where NR_p is the amount of NOx removed from each plant/boiler (in tonnes); AE_t is the abatement efficiency of the control technology t used; MW_p is the plant capacity. The parenthesis in the bracket is the total annual NO_x emissions for a given fuel type f in each sector j and for each European country i, where D_{ijf}, is the demand for the fuel f in sector j and country i; N_{if} is the nitrogen content of fuel f in country i; R_f, is the retention factor of fuel f, i.e. nitrogen retained in ash. R_f is dependent on many factors, including boiler type, firing temperature, ash content and calcium/sodium content of the fuel and varies by fuel. To derive the emissions per MW, the total annual emissions in a country i, sector j and fuel f (NE_{ijf}) are divided by the total capacity (in MW_e) of plants in country i, sector j and fuel type f (MW_{ijf}).

For mobile sources costs and emission reductions are summed over the whole lifecycle and the amount of NO_x abated is found by multiplying the annual average fuel consumption, the abatement efficiency of the control method, the emission factor for unabated emissions and vehicles' lifetimes.

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