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LONG-RANGE TRANSBOUNDARY AIR POLLUTION

Working Group on Abatement Techniques

CONTROL TECHNIQUES FOR EMISSIONS OF NO_x FROM STATIONARY SOURCES

Prepared by the Task Force on the Assessment of
Control Options/Techniques for NO_x, led by Germany */

Introduction

1. This document covers the stationary sources of NO_x emissions listed in table 1.

2. The aim of this document is to provide Parties to the Convention with guidance on identifying best available techniques to enable them to meet the obligations of the Protocol. The presented options for best available techniques (BAT) can be applied in general.

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*/ At the fifth meeting of the Task Force held in Karlsruhe (Germany) from 21-22 October 1998.

Table 1: Considered stationary source categories for NO_x emissions

Source categories
1. Combustion installations (a) Boilers (b) Gas turbines (c) Stationary engines
2. Mineral oil refineries
3. Coke oven furnaces
4. Production and processing of metals: - Metal ore roasting or sintering installations - Installations for the production of pig iron or steel (primary or secondary fusion) including continuous casting - Installations for the processing of ferrous metals (hot rolling)
5. Installations for the production of cement clinker in rotary kilns or in other furnaces
6. Installations for the manufacture of glass including glass fibre
7. Installations for the production of nitric acid
8. Installations for the incineration of municipal waste, hazardous waste, medical waste and sludges from waste-water treatment

3. This document is based on options and techniques for NO_x emission prevention and reduction and their performance and costs as documented in the technical background report prepared by the Task Force on the Assessment of Abatement Options/Techniques for NO_x which includes information provided to the lead country by plant operators, producers of NO_x control equipment and members of the Task Force. The technical background report is also based on information from official documentation of the Executive Body and its subsidiary bodies, e.g. the documentation of the Sixth Seminar on Control Technologies for Emissions from Stationary Sources held in 1996 in Budapest, and other published information. It gives the present status (April 1998) of development and application of the relevant options and techniques and related costs for the reduction of NO_x emissions from stationary sources in the main emitting source categories.

4. 'Best available techniques' means the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole:

(i) 'Techniques' includes both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned;

(ii) ‘Available' techniques means those techniques developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Party in question, as long as they are reasonably accessible to the operator;

(iii) 'Best' means most effective in achieving a high general level of protection of the environment as a whole.

In determining the best available techniques, special consideration should be given, generally or in specific cases, to the factors below bearing in mind the likely costs and benefits of a measure and the principles of precaution and prevention:

(a) The use of low-waste technology;

(b) The use of less hazardous substances;

(c) The furthering of recovery and recycling[1/] of substances generated and used in the process and of waste where appropriate;

(d) Comparable processes, facilities or methods which have been tried with success on an industrial scale;

(e) Technological advances and changes in scientific knowledge and understanding;

(f) The nature, effects and volume of the emissions concerned;

(g) The commissioning dates for new or existing installations;

(h) The length of time needed to introduce the best available technique;

(i) The consumption and nature of raw materials (including water) used in the process and their energy efficiency;

(j) The need to prevent or to reduce to a minimum the overall impact of the emissions on the environment and the risks to it;

(k) The need to prevent accidents and to minimize the consequences for the environment.

5. This document addresses the control of NO_x emissions considered as the sum of nitrogen oxide (NO) and nitrogen dioxide (NO_2) expressed as NO_2. However, when measures or techniques are planned for NO_x sources emitting other components and, in particular, sulphur oxides (SO_x), volatile organic compounds (VOCs), ammonia (NH_3), greenhouse gases (such as CO_2 and N_2O), particulates (including heavy metals), and persistent organic pollutants (POPs), it is worthwhile to consider them together with such other pollutant-specific control options in order to maximize the abatement effect and minimize the impact on the environment. Respective trade-offs between different pollutants have to be accounted for. This is particularly important for multi-pollutant/multi-effect approaches.

I. GENERAL ISSUES

6. Several possibilities exist to control or to prevent NO_x emissions from stationary sources. Primary, secondary (add-on or end-of-pipe) and structural measures are generally distinguished. If not stated otherwise, measures are applicable to existing and new installations. The following list gives a general outline of available measures, which may also be combined:

(a) Enhanced effectiveness of existing NO_x control technologies;

(b) Energy management (efficient and rational use of energy);

(c) Appropriate boiler design;

(d) Improved combustion technologies;

(e) Combustion modification (primary measures);

(f) New concepts for combustion technologies;

(g) Flue gas cleaning (secondary measures);

(h) Good housekeeping (e.g. good maintenance, good control).

A. Structural measures

7. The use of clean fuels and the rational use of energy result in a reduction in NO_x emissions. Usually, the use of certain fuels is governed by a country’s energy supply structure. Thus, the use of low NO_x producing fuels is usually limited. Although there is a substantial technical potential for reducing NO_x by fuel switching, achieving this potential will depend on country-specific conditions such as its infrastructure and policy. On the other hand, substantial reductions in energy consumption may be achieved in many production processes through energy management, e.g. energy conservation, technology switch, and demand-side management. The costs of energy management options may be lower than the costs of additional energy supply. Energy management can contribute substantially to the mitigation of air pollution. Fuel cleaning for fuel nitrogen removal is not a commercial option. Increasing the application of hydroprocessing in refineries, however, also brings about a reduction in the nitrogen content of the end product.

B. Primary and secondary measures

8. To achieve the most efficient NO_x reduction, beyond energy management measures, a combination of technical options (fuel switching, other combustion technologies, process and combustion modifications, flue gas treatment) should be considered. Furthermore, to identify the best combinations of combustion modifications and flue gas treatment, site-specific evaluation is needed, in order to meet given emission targets.

9. Process and combustion modifications are applied to reduce the formation of NO_x during combustion. They include the control of combustion air ratio, flame temperature, fuel-to-air ratio, etc. Some of the options are typical for retrofit; others are typical for new installations, but may also be applied to retrofit. Efficiency and applicability could have some limitations. These measures are widely implemented, either singly or in combination:

(a) Low excess air combustion (LEA);
(b) Reduced air preheat (RAP);[2/]
(c) Burner-out-of-service (BOOS);[2/]
(d) Biased-burner-firing (BBF);[2/]
(e) Low NO_x burners (LNB);
(f) Flue gas recirculation (FGR);
(g) Over fire air combustion (OFA);
(h) In-furnace NO_x reduction or reburning (IFNR);
(i) Water/steam injection and lean/premixed combustion.[3/]

10. NO_x control technologies such as reburning are well developed and available for all combustible fuels. The achievable removal efficiency is reported to reach 70 - 80%, alone or in combination with other primary measures. Reburning offers some advantages such as compatibility with other primary NO_x emission reduction measures, simple installation, use of a standard fuel (oil, gas) as reducing agent, no additives and little additional energy required. Especially the successful implementation of reburning in large oil-fired units has to be mentioned, as well as the experience with coal as a reduction agent. The trend nowadays is to use the same fuel as fuel and reducing agent.

11. NO_x emissions can be also reduced by using inherent low NO_x control technologies such as fluidized bed combustion. This technology is applicable to a large range of fuels (coal, biomass, residues, etc.). Due to the rather low combustion temperature (about 850°C) and an inherent air staging, this technology achieves low NO_x emissions and can generally be used without secondary measures. Oxycombustion is another way of abating NO_x emissions; until now, industrial applications of this technique have been limited to glass manufacturing.

12. Basic combustion modifications are incorporated mainly into boiler and burner design. For example, modern furnace designs incorporate OFA devices. The latest generation of LNB combines both air-staging and fuel-staging (reburning at burner level).

13. Unlike most combustion processes, the application of combustion and/or process modifications in industrial processes with combustion has many process-specific limitations. In cement kilns or glass melting furnaces, for example, certain high temperatures and homogeneous temperature distributions are necessary to ensure product quality. Typical combustion modifications being used are staged combustion/low NO_x burners, flue gas recirculation and process optimization (e.g. precalcination in cement kilns).

14. The selective catalytic reduction process (SCR) is the most mature and widely implemented flue gas treatment process with a high removal efficiency (in some sectors, this efficiency can, depending on the case, reach up to 95% and high availability. The SCR process usually uses ammonia or urea as a reducing agent, but the use of high-pressure stored anhydrous ammonia is the most common. Many SCR installations using these additives are being operated successfully in Europe, mostly for boilers. Application of SCR at gas-fired plants can reduce NO_x emissions to very low levels. It has been implemented at gas, oil, and coal-fired installations. Catalyst lifetimes are much higher than initially projected and have reached as much as 6 – 10 years for coal-fired units, and 8 – 12 years for gas- and oil-fired units, the lower values being achieved for high-dust configuration and the higher for tail-gas configuration. SCR is applicable also to smaller combustion installations and it is a well established de-NO_x technology for combustion in boilers and for certain industrial processes, such as:

(a) Nitric acid plants;
(b) Glass smelters;
(c) Cement production (the applicability of SCR is currently being tested on a pilot scale);
(d) Refinery furnaces;
(e) Combustion of hazardous wastes (usually in rotary kilns);
(f) Combustion of municipal wastes (usually in grate furnaces);
(g) Combustion of hospital and other special wastes in public or industrial units (rotary kilns, pyrolysis plants, fluidized bed incineration of industrial wastes like sludges, rejects, production residues) also in rather small units (< 10 MW_{th}).

15. The selective non-catalytic reduction process (SNCR) is applicable to small and medium-sized installations with medium raw gas NO_x contents. The SNCR process is implemented in a variety of combustion installations and process furnaces (glass and cement production) as well as in waste incinerators. The SNCR process is in general capable of 30 – 70% reductions. Combined with flue gas recirculation, it is an attractive and reliable technology for moderate NO_x removal (50 - 80%), especially for smaller combustion plants and industrial processes.

16. Other flue gas treatment technologies are the combined NO_x/SO_2 removal processes. The activated carbon process (AC) is an option used in few cases only, since it is expensive and leads to limited NO_x reduction (around 60%). The SNOX process, which removes both sulphur oxides and nitrogen oxides, offers some advantages in the case of high-sulphur feedstocks.

C. <u>Costs</u>

17. The estimation of investments and operating costs for NO_x emission reduction options/techniques is important when choosing from the wide range of measures and, on a more macroeconomic level, when developing an emission control strategy on national or regional level. A detailed assessment of cost data in terms of consistent investment and operating costs is presented in the background document on best available techniques of the Task Force on the

Assessment of Abatement Options/Techniques for NO_x. The respective data are based on practical experience. Data have been collected for existing and new plants; for the latter, the investment can usually be considerably lower.

18. Examples of investments and operating costs are given in table 2 for selected relevant combinations of primary and secondary measures, which are applicable in the considered sectors. The examples are specific for detailed relevant parameters, such as yearly operating hours, waste gas volume flow and pollutant concentration therein, capacity of the base installation, fuel type, etc. Thus, the given data serve an illustrative purpose and cannot be taken as generally applicable values. In table 3, the most important parameters are given for the determination of operating costs for the example of SCR. These examples illustrate the methodology followed for the cost assessment in the technical background report of the Task Force on the Assessment of Abatement Options/Techniques for NO_x.

Table 2: Investments and operating costs of control options for the abatement of NO_x emissions (retrofit of existing installations)

Characteristics of reference installation	Control options	Invest-ments[a)] [ECU]	Operating Costs[b)] [ECU/a]	Abated mass flow [Mg NO_x/a]
Boilers				
Public power and district heating; Boiler; Fuel: hard coal; Capacity: 1,500 MW_{th}; Operating time: 5,500 h/a	Low NO_x burner	13,300,000	1,400,000	3,560
	Low NO_x burner & over-fire air	16,100,000	1,500,000	4,100
	Low NO_x burner & SCR	61,300,000	6,400,000	8,110
	Low NO_x burner& over-fire air & SNCR	17,500,000	2,200,000	6,770
	Low NO_x burner & over-fire air & SCR	64,100,000	6,500,000	8,200
Public power and district heating; Boiler; Capacity: 600 MW_{th}; Fuel: hard coal; Operating time: 1,500 h/a	Low NO_x burner	7,000,000	430,000	390
	Low NO_x burner & over-fire air	8,500,000	505,000	450
	Low NO_x burner & SCR	32,000,000	1,930,000	885
	Low NO_x burner& over-fire air & SNCR	9,200,000	610,000	740
	Low NO_x burner & over-fire air & SCR	33,500,000	2,000,000	895
Industry; Boiler; Fuel: natural gas; Capacity: 160 MW_{th}; Operating time: 6,000 h/a	Low NO_x burner	2,800,000	170,000	140

Characteristics of reference installation	Control options	Invest-ments[a)] [ECU]	Operating Costs[b)] [ECU/a]	Abated mass flow [Mg NO_x/a]
Industry; Boiler; Fuel: plant gas; Capacity: 160 MW_{th}; Operating time: 6,000 h/a	Low NO_x burner & SNCR	1,500,000	240,000	830
	Low NO_x burner & SCR	3,400,000	560,000	1,040
	Flue gas recirculation & SNCR	1,300,000	210,000	780
	Flue gas recirculation & SCR	3,200,000	530,000	1,030
	Low NO_x burner & flue gas recirculation & SNCR	2,000,000	310,000	920
	Low NO_x burner & flue gas recirculation & SCR	3,850,000	630,000	1,070
Public power, district heating, industry; Circulating fluidized bed combustion: Fuel: coal; Capacity: 160 MW_{th}; Operating time: 6,000 h/a	No measure	10,700,000 [c/]	830,000 [c]	760 [c/]
	SNCR	290,000	74,000	152
Commercial and institutional heating; Boiler; Fuel: heavy fuel oil; Capacity: 5 MW_{th}; Operating time:2,000 h/a	Low NO_x burner	245,000	13,000	3.1
	Over-fire air	51,000	2,500	0.75
	Low NO_x burner & overfire air	295,000	15,700	3.6
	Low NO_x burner & flue gas recirculation	295,000	16,500	4.5
Gas turbines				
Combined cycle; Output capacity: 150 MW_{el}; Fuel: natural gas; Working time: 6,000 h/a	PM	2,050,000	370,000	670
	SCR	27,000,000	3,110,000	1,145
Simple cycle; Output capacity: 30 MW_{el}; Fuel: natural gas; Working time: 2,000 h/a	PM	360,000	36,000	70
	SCR	5,400,000	380,000	115
	PM & SCR	4,000,000	300,000	125
Cogeneration plant in industry; Output capacity of gas turbine: 25 MW_{el}; Fuel: diesel oil; Working time: 8,000 h/a	PM	550,000	50,000	685
	SCR	4,500,000	600,000	1,165
	PM & SCR	5,050,000	610,000	1,265

Characteristics of reference installation	Control options	Invest-ments[a)] [ECU]	Operating Costs[b)] [ECU/a]	Abated mass flow [Mg NO_x/a]
IGCC [d/]; Output capacity: 450 MW_{el}; Fuel: heavy fuel oil; Working time: 8,000 h/a	PM	5,400,000	700,000	4,000
	SCR	81,000,000	10,000,000	6,900
Stationary engines				
Old rich burn gas engine; Fuel: natural gas; Output capacity: 600 kW_{el}; Working time: 5,000 h/a	Lean burn	10,000	- 3,000	40
	[NSCR]	[40,000]	[2,500]	[40]
Improved lean burn gas engine; Fuel: natural gas; Output capacity: 600 kW_{el}; Working time: 5,000 h/a	SCR	50,000 [e/]	15,000	5
Diesel engine; Fuel: heavy fuel oil; Output capacity: 20 MW_{el}; Working time: 5,000 h/a	SCR	230,000	40,000	650
Diesel engine; Fuel: diesel oil; Output capacity: 3 MW_{el}; Working time: 5,000 h/a	Exhaust gas recirculation	15,000	5,000	26
	SCR	230,000	40,000	78
	Exhaust gas recirculation & SCR	245,000	40,000	80
Diesel engine; Fuel: heavy fuel oil; Output capacity: 20 MW_{el}; Working time: 5,000 h/a	SCR	60,000	9,000	100
Iron and steel production: sinter plants				
Travelling grate sinter machine; Fuel: coke breeze; Production output: 12,000 Mg sinter/d; Working time: 8,400 h/a	Flue gas recirculation	5,000,000	- 200,000 [f/]	2,000
	SCR	50,000,000	10,000,000	6,600
	Flue gas recirculation & SCR	48,000,000	5,000,000	6,700

Characteristics of reference installation	Control options	Invest-ments[a)] [ECU]	Operating Costs[b)] [ECU/a]	Abated mass flow [Mg NO_x/a]
Cement production				
Dry process with preheater/precalciner; Fuel: coal; Production capacity: 2,000 Mg/D; Working time: 5,000 h/a	Low NO_x burner and staged combustion for precalciner kiln	3,600,000	240,000	340
	Low NO_x burner and SNCR	2,175,000	340,000	460
Dry process with preheater/precalciner; Fuel: coal; Production capacity: 2,000 Mg/d; Working time: 8,000 h/a	Low NO_x burner and SCR	6,400,000	820,000	960
Glass production: container glass				
Production of flint and coloured glass; Regeneratively heated furnace; Fuel: natural gas; Production capacity: 400 Mg/d; Working time: 8,760 h/a	CM [g/]	600,000	30,000	300
	Reburning	250,000	200,000	470
	LoNO$_x$ melter	2,000,000	100,000	550
	Oxycombustion	- 1,200,000 [h/]	1,200,000	630
	SNCR	1,000,000	130,000	390
	SCR	4,000,000	500,000	550
	CM & SNCR	1,580,000	161,000	550
	CM & SCR	4,390,000	536,000	650
Production of flint and coloured glass; Recuperatively heated furnace; Fuel: natural gas; Production capacity: 400 Mg/d; Working time: 8,760 h/a	CM [g/]	360,000	18,000	76
Nitric acid production				
Production of medium concen-tration nitric acid High dual pressure plant; Production capacity: 1,000 Mg/d; Working time: 8,400 h/a	SCR	2,000,000	300,000	950
Production of high concentration nitric acid; Production capacity: 500 Mg/d; Working time: 8,400 h/a	SCR	1,200,000	200,000	800

Characteristics of reference installation	Control options	Invest-ments[a)] [ECU]	Operating Costs[b)] [ECU/a]	Abated mass flow [Mg NO_x/a]
Waste incineration: incineration of domestic or municipal wastes				
Moving grate incinerator; rotary kiln Capacity: 30 Mg/d; Operating time: 8,400 h/a	PM [i/]	300,000	30,000	100
	SNCR	1,000,000	200,000	350
	SCR	26,000,000	2,000,000	430
	PM & SNCR	1,300,000	230,000	380
	PM & SCR	26,300,000	2,000,000	440

a/ Depending on e.g. waste gas flow rate, production capacity, peripheral conditions
b/ Depending on e.g. waste gas flow rate, NO_x inlet concentration in the waste gas, annual operating time, NO_x reduction rate, etc.
c/ Compared with conventional pulverized coal combustion.
d/ Limited operating experience.
e/ Including a small oxidation catalyser
f/ Due to reduced coke breeze consumption.
g/ E.g. low excess air, reduced air preheating, staged combustion.
h/ Compared to conventional air combustion.

PM = Primary Measure
CM = Combustion Modification
SNCR = Selective Non Catalytic Reduction
SCR = Selective Catalytic Reduction
NSCR = Non Selective Catalytic Reduction (three-way catalyser)

Table 3: Major cost components and related parameters considered for the assessment of operating costs (ECU/a) for the SCR technology (for aqueous ammonia)

Parameters 6 Main cost components 9	**Waste gas flow rate**	**C (NO_x, in)**	**Annual working time (h/a)**	**NO_x reduction**	**Share of NO in total NO_x**	**Rela-tive impor-tance**
Direct consumption related operating costs						
Ammonia consumption[a/]	!	!	!	!	!	++
Electricity consumption[a/]	!		!			++
Fuel consumption[b/]	!		!			+
Catalyst replacement[a/]	!		!			+++
Personnel			!			+
Investment-related operating costs						
Maintenance and repair	!	!		!		++
Taxes	!	!		!		+
Insurance	_!	!		!		+

C (NO_x, in) = inlet NO_x-concentration in flue gas
[a/] Dominating items together with capital costs (not taken into account in table 3).
[b/] To be considered in the case of tail gas or low dust configuration

Concerning the investment-related costs, it should be taken into account that depreciation and interest (capital costs) represent the most important cost items (not taken into account in table 3) for the SCR technology.

19. To derive the abatement cost per sector for a given country, it is necessary to consider parameters such as:

- Capacity distribution of production processes;
- Age distribution and final lifetime of production processes;
- Transition periods/implementation schedules with regard to technology changes;
- Production and abatement technologies already in place according to current legislation;
- Future activity rates of sectors;
- Nature of raw materials, process design and operation.

To derive this information, substantial further analysis than table 3 provides is needed. The background document provides the reference installation methodology and the necessary data (investments, annual operating costs) taking into account the set of relevant parameters mentioned above to assess these costs.

20. To improve national cost functions, they should adequately reflect the individual country’s situation. Therefore, in a bottom-up approach, the country-specific ranking of options for the various sectors should be combined with country-specific activity levels. Finally, the national cost functions should be the result of an optimization consideration how to adapt the production system over time to different NO_x reduction requirements. This includes not only end-of-pipe measures, but also structural changes within the sectors.

D. <u>Side effects</u>

21. Side effects of emission abatement options/techniques should be accounted for. Particular attention should be paid to the influence of NO_x control measures on related air pollution issues such as ammonia emissions released from certain emission reduction facilities. Moreover, cross-media aspects should be considered in terms of water pollution and waste generation which may be induced or increased by certain NO_x emission reduction options/techniques. However, these side effects can generally be limited by proper design and operation of the facilities. More specifically, the side effects to be considered with different emission reduction techniques are:

(a) Combustion modifications: possible side effects are decrease in overall energy efficiency, increased CO formation and hydrocarbon emissions, corrosion due to reducing atmosphere, increase of unburnt carbon in fly ash;

(b) FBC: this technique also brings about a considerable reduction in SO_x emissions. A possible drawback in FBC systems may be the increased formation of N_2O under certain process conditions. The handling of the ashes needs consideration in relation to their possible use and/or disposal;

(c) SCR: some possible side effects are ammonia slip in the exhaust gas, ammonia content in the fly ash, formation of ammonium salts on downstream facilities, deactivation of the catalyst and increased conversion of SO_2 to

SO_3 (corrosion). By the controlled operation of the plant, the fly ash quality can, however, be guaranteed and the formation of ammonia salt reduced. In terms of by-products, deactivated catalysts from the SCR process may be the only relevant products, although this has become a minor problem since the catalyst lifetime has been improved and reprocessing options exist;

(d) SNCR: side effects to be considered are ammonia in the exhaust gas, formation of ammonium salts on downstream facilities, the formation of N_2O, when urea, for instance, is used as a component of the reducing mixture, and CO releases;

(e) The reagent production of ammonia and urea for flue gas treatment processes involves a number of separate steps which require energy and reactants. The storage systems for ammonia are subject to the relevant safety legislation and such systems are designed to operate as totally closed systems, with a resultant minimum of ammonia emissions. The use of NH_3 is still considered appropriate, even when taking into account the indirect emissions related to the production and transport of NH_3.

III. <u>SECTOR-SPECIFIC ISSUES</u>

A. <u>Combustion installations</u>

22. This section covers boilers, (small: 1 – 10 MW_{th}, medium: 10 – 50 MW_{th}, and large: > 50 MW_{th}), gas turbines (> 1 MW_{el}), and stationary engines (> 100 kW_{el}). Given capacity classes in terms of rated thermal input refer to the lower heating value (LHV) of the respective fuel.

23. New concepts for combustion technologies with improved thermal efficiency and reduced NO_x emissions include combustion turbines, atmospheric and pressurized fluidized bed combustion, integrated gasification combined cycle, combined cycle gas turbines, cogeneration and supercritical boilers:

(a) Stationary combustion turbines can also be integrated in existing conventional power plants (known as topping). The overall efficiency can be increased by 5 – 6%, but the achievable NO_x reduction will depend on site-specific conditions. Major alterations to the existing boiler system may become necessary;

(b) Fluidized bed combustion (FBC) is a combustion technology for burning hard coal and lignite, but also low-grade fuels such as waste, peat and wood. Emissions can be further reduced through integrated combustion control in the system. Within the sector of energy conversion, atmospheric fluidized bed combustion is a well established commercial technology. There are more circulating fluidized bed combustors than bubbling fluidized bed combustors. Currently, more than 200 circulating fluidized bed systems with a total capacity of about 26,000 MW_{th} and 15 pressurized fluidized bed systems (representing about 5,000 MW_{th}) are in operation worldwide;

(c) The integrated gasification combined cycle (IGCC) process incorporates coal gasification and combined cycle power generation in a gas and a steam turbine. The gasified coal is burned in the combustion chamber of the gas turbine. The technology also exists for heavy oil residue. The installed capacity at present is about 1,000 MW_{th} (5 plants). However, this process is not yet fully commercialized;

(d) Combined cycle gas power stations using advanced gas turbines with an overall energy efficiency significantly higher than 55 % and with reduced NO_x emissions are being built;

(e) The combined generation of electricity and heat in so-called cogeneration plants represents a possibility to save fuel (up to 50% reduction in energy consumption compared to separate generation of electricity and heat). Although the electrical efficiency is decreased by the extraction of steam, the overall efficiency of the cogeneration system ranges between 70 and 90%;

(f) A further measure to increase conventional power plant efficiency is the use of supercritical steam cycle conditions. Total system net energy efficiencies can achieve 43% for hard coal fired plants, 41% for lignite-fired plants, and 56% for gas-fired combined cycle plants.

24. Table 4 gives a selection of applicable abatement options and the respective clean gas concentrations achievable by typical emission sources.

Table 4: Emission sources and selected NO_x control measures with their respective clean gas concentrations for combustion installations

Emission source	Combination of control measures	Clean gas concentration (mg/Nm^3)
Small boilers 1 - 10 MW_{th}, medium boilers 10 - 50 MW_{th}		
Dry bottom boiler; Fuel: hard coal (> 10 MW_{th})	Primary measures (PM)	400 - 600
Boiler; Fuel: light fuel oil	PM	150 - 300
Boiler; Fuel: heavy fuel oil	PM	300 – 600
Boiler; Fuel: natural gas	PM	50 – 150
Circulating FBC; Fuel: coal, peat, biomass, etc.	no further measure	150 - 300
Bubbling FBC; Fuel: coal, bark, oil, sediment, etc.	no further measure	200 - 400
Industrial boiler; Fuel: process gas	PM	100 - 300
Large boilers > 50 MW_{th}		
Dry bottom boiler	PM	300 – 600
Fuel: hard coal	PM and SCR (many applications)	80 - 150
	PM and SCR (many applications	
Boiler	PM (without reburning)	250 –500
Fuel: heavy fuel oil	PM (incl. reburning)	# 200

Emission source	Combination of control measures	Clean gas concentration (mg/Nm^3)
	PM and SCR	60 - 150
Boiler; Fuel: natural gas	PM	50 - 200
Wet bottom boiler Fuel: hard coal	PM and SCR (tail gas)	# 150
	PM and SNCR	# 200
Pressurized FBC Fuel: hard coal	no further measure	150 - 200
	SCR and/or SNCR	# 100
Circulating FBC Fuel: coal, peat, biomass, etc.	no further measure	150 - 300
	SNCR	100 - 200
Bubbling FBC; Fuel: coal, bark, oil, sediment, etc.	no further measure	200 - 400
	SNCR	130 - 200
Industrial boiler Fuel: process gas	PM	100 - 300
	PM and SCR	100 - 200
Gas turbines		
Simple cycle, combined cycle, cogeneration (prior to supplementary firing), mechanical drive		
Fuel: natural gas	PM	50 – 150 [400]*
	SCR	10 – 50
Fuel: diesel oil or process gas	Wet controls	100 - 200
	SCR	20 - 100
IGCC		
Fuel: coal or heavy fuel oil	Nitrogen and steam injection	50 - 100
Stationary engines		
Spark ignition (= Otto) engines, 4-stroke		
Old rich burn	NSCR (three-way catalyser)	350
Improved lean burn	No measure	300 - 550
	SCR	100
Compression ignition (= Diesel) engines		
Fuel: heavy fuel oil	SCR	[200; 400 – 1,000]
Fuel: diesel oil	SCR	360 - 500
	Exhaust gas recirculation and SCR	180 - 240

Boilers: Solid fuels: 6% excess O_2; Liquid fuels: 3% excess O_2; Gaseous fuels: 3% excess O_2
Gas turbines: 15% excess O_2; **Stationary engines:** 5% excess O_2
Values apply to different raw gas concentrations and are valid for baseload operation of the considered utilities.
PM: Primary Measures NSCR: Non-Selective Catalytic Reduction (three-way catalyser)

* For simple cycle

B. Mineral oil refineries

25. This section addresses combustion processes in mineral oil refineries without contact between flame or flue gas and products. The most relevant sources of NO_x emissions in mineral oil refineries are process heaters for the heating of crude oil and petroleum products.

26. A significant part of the fuel used for process heaters is provided by refinery gas. Various processes contribute a large variety of compounds to the refinery gas, resulting in varying NO_x emissions. Other fuels in use in mineral oil refineries are natural gas, petroleum coke, heavy fuel oil, or other residues originating from atmospheric and vacuum distillation, fluid catalytic cracking (FCC) and thermofor catalytic cracking (TCC). Table 5 gives a selection of applicable abatement options and the respective clean gas concentrations achievable by typical emission sources.

Table 5: Emission sources and selected NO_x control measures with respective clean gas concentrations in mineral oil refineries

Emission source	**Combination of control measures**	**Clean gas concentration (mg/Nm^3)**
Process heater; Fuel: petroleum coke	Primary measures (PM)	# 200
Process heater; Fuel: heavy fuel oil	PM	250 - 600
Process heater; Fuel: natural gas	PM	50 - 200
Process heater; Fuel: process gas	PM	100 - 300
FCC	SCR	100 - 200

Solid fuels: 6% excess O_2; liquid fuels: 3% excess O_2; gaseous fuels: 3% excess O_2
Values apply to different raw gas concentrations.

C. Coke oven furnaces

27. This section deals with emissions originating from coke oven furnaces in iron and steel production. Table 6 gives a selection of applicable abatement options and the respective clean gas concentrations achievable by typical emission sources.

Table 6: Emission sources and selected control measures with respective clean gas concentrations for coke oven furnaces in iron and steel production

Emission source	Combination of control measures	Clean gas concentration (mg/Nm^3)
Fuel: coke oven gas	Combustion modification* and SCR	# 60
Fuel: blast furnace gas	SCR	# 10

Gaseous fuels: 3% excess O_2.
Values apply to different raw gas concentrations.
* Waste gas recirculation, air-staged combustion, lowering the coking temperature.

D. **Production and processing of metals**

28. This section deals with emissions originating from sinter plants, blast furnace cowpers, and reheating furnaces in iron and steel production. Until now, no NO_x-removal option has been applied to blast furnace cowpers. Direct reduction and direct smelting are currently under development and may reduce the need for sinter plants and blast furnaces in the future. The application of these technologies depends on the ore characteristics and requires the resulting product to be processed in an electric arc furnace. Table 7 gives a selection of applicable abatement options and the respective clean gas concentrations achievable by typical emission sources.

Table 7: Emission sources and selected control measures with respective clean gas concentrations for sinter plants and reheating furnaces in iron and steel production

Emission source	Combination of control measures	Clean gas concentration (mg/Nm^3)
Sinter plants		
Travelling grate; Fuel: coke breeze	Flue gas recirculation and SCR	# 230
Reheating furnaces		
Fuel: blast furnace gas	Low NO_x burner	# 390
Fuel: coke oven gas, heavy fuel oil	Low NO_x burner	# 1,100
Fuel: natural gas, gas oil	Low NO_x burner	# 250

Solid fuels: 6% excess O_2; liquid fuels: 3% excess O_2; gaseous fuels: 3% excess O_2.
Values apply to different raw gas concentrations.

E. Cement production

29. Cement kilns make use of fossil as well as secondary fuels such a waste oil or waste tyres. For the production of clinker, several kiln types are available, showing different NO_x emission levels: long wet rotary kiln, long dry rotary kiln, dry rotary kiln with cyclone/grate preheater, dry rotary kiln with cyclone/grate preheater and precalciner, shaft furnace. In terms of energy demand and emission control opportunities, dry rotary kilns with cyclone/grate preheater and precalciner are preferable. In Europe, the dry process is mostly used, especially in new plants. In modern dry process kiln systems, the precalciner technology is used to further improve, among other things, thermal efficiency and production capacity.

30. Table 8 gives a selection of applicable abatement options and the respective clean gas concentrations achievable by typical emission sources. In the last years, the selective catalytic reduction process has been implemented at several demonstration plants on a pilot scale. SCR is not yet current practice in the cement manufacturing sector. However, given the recent positive experience, it may become an applicable control option in the future.

Table 8: Emission sources and selected NO_x control measures with their respective reduction efficiencies and clean gas concentrations in cement production

Emission source	Combination of control measures	Clean gas concentration (mg/Nm^3)
Dry process with preheater/precalciner		
Fuel: coal	Low NO_x burner and staged combustion for precalciner kiln	# 1,000
	Low NO_x burner and SNCR	200 - 800
	Low NO_x burner and SCR	100 - 200
Solid fuels: 10% excess O_2. Values apply to different raw gas concentrations.		

F. Glass production

31. This section deals with the production of flat and container glass, glasswool, commodity glass (TV screen, lighting) and domestic glassware. In glass production, several parameters have a significant influence on the NO_x emission levels: the type of fuel used (natural gas, heavy fuel oil), the furnace type (cross-fired, end-fired furnaces; regenerative, recuperative air preheating) and the type of glass produced (flint glass, clear glass, tint glass).

32. Table 9 gives a selection of applicable abatement options and the respective clean gas concentrations achievable by typical emission sources. In the last years, some promising abatement technologies have emerged: reburning and oxycombustion. When using oxycombustion, special care has to be

taken with regard to energy efficiency so as not to reduce the NO_x emission abatement potential.

Table 9: Emission sources and selected NO_x control measures with their respective reduction efficiencies and clean gas concentrations in glass production

Emission source	Combination of control measures	Clean gas concentration (mg/Nm^3)
Flat glass		
Clear glass		
Cross-fired furnace with regenerative preheating; Fuel: natural gas	Combustion modification[a] and low NO_x burner and SCR	# 500
Cross-fired furnace with regenerative preheating; Fuel: natural gas or heavy fuel oil	Reburning	# 500
Cross-fired furnace with regenerative preheating; Fuel: heavy fuel oil	Combustion modification (primary measures)	# 600
Tinted glass		
Cross-fired furnace with regenerative preheating; Fuel: natural gas	Combustion modification[a] and low NO_x burner and SCR	# 700
Cross-fired furnace with regenerative preheating; Fuel: natural gas or heavy fuel oil	Reburning	# 500
Container glass		
Regeneratively heated furnace; Fuel: natural gas	Low NO_x burner and SCR	# 350
	Combustion modification[a] and low NO_x burner and SNCR	# 600
	Oxycombustion[b]	# 400
	Reburning	# 500
Regeneratively heated furnace; Fuel: heavy fuel oil	Combustion modification[a] and low NO_x burner and SNCR	# 450
	Oxycombustion[b]	# 300
	Reburning	# 500
Recuperatively heated furnace; Fuel: natural gas	Combustion modification (primary measures)	# 350
Glass wool		
Recuperatively heated furnace; Fuel: natural gas	Oxycombustion[b]	# 300
Regeneratively heated furnace; Fuel: heavy fuel oil	Oxycombustion[b]	# 250

Emission source	Combination of control measures	Clean gas concentration (mg/Nm³)
Special glass		
Commodity glass		
Recuperatively heated furnace;	Combustion modification[a] and low NO_x burner and SNCR	# 600
Fuel: natural gas	Oxycombustion[b]	# 400
Recuperatively heated furnace;	Combustion modification[a] and low NO_x burner and SNCR	# 450
Fuel: heavy fuel oil	Oxycombustion[b]	# 300
Solid, liquid and gaseous fuels: 8% excess O_2. Values apply to different raw gas concentrations. [a] E.g. low excess air, reduced air preheating, staged combustion. [b] Related to total NO_x emission mass flow for comparison.		

G. Nitric acid production

33. For the production of nitric acid, two production methods exist: the first produces medium-concentration nitric acid (50 – 75 wt.-%), the second leads to high-strength nitric acid (98 wt.-%), which can be achieved either by direct process or extractive distillation (via medium-concentration nitric acid). The most relevant process in terms of NO_x emissions is the production of medium-concentration nitric acid. Traditionally, medium-concentration nitric acid production plants are designed either as low-pressure, medium-pressure or high-pressure. The state of the art for new plants is medium-pressure equipped with selective catalytic reduction, and high-pressure plants.

34. Table 10 gives achievable clean gas concentrations for typical emission sources when applying selective catalytic reduction.

Table 10: Emission sources and selected NO_x control measures with their respective clean gas concentrations in nitric acid production

Emission source	Combination of control measures	Clean gas concentration (mg/Nm³)
Production of medium concentration nitric acid		
Medium dual pressure	SCR	# 400
High dual pressure	SCR	# 100
Production of medium- and high-concentration nitric acid (extractive distillation process)		
Medium dual pressure	SCR	# 240
Production of high-concentration nitric acid		
Direct process or extractive distillation	SCR	# 180
The given concentrations refer to the production step only (not to the concentration step) and to 3% O_2.		

H. Waste incineration

35. This section addresses the incineration of municipal (or domestic), hazardous and medical wastes as well as the incineration of sludges from waste-water treatment. Different incineration technologies generate different levels of NO_x emissions (e.g. moving grate, rotary kiln, fluidized bed combustion, electric infrared).

36. Emissions of NO_x can generally be reduced by reducing the amount of incinerated waste. This can be accomplished through various waste management stra-tegies, including recycling programmes and composting of organic materials.

37. The most relevant technologies for reducing NO_x emissions are flue gas recirculation, air-staged combustion, SCR and SNCR. Table 11 gives a selec-tion of applicable abatement options and the respective clean gas concentra-tions achievable by typical emission sources.

Table 11: Emission sources and selected NO_x control measures with their respective clean gas concentrations in waste incineration

Emission source	**Combination of control measures**	**Clean gas concentration (mg/Nm³)**
Domestic or municipal waste incineration		
Moving grate, rotary kiln	Primary measures (air staging)	# 250
	Flue gas recirculation or air-staged combustion and SNCR	# 140
	Flue gas recirculation or air-staged combustion and SCR	# 70
Fluidized bed combustion	Flue gas recirculation or air-staged combustion and SNCR	# 80
	Flue gas recirculation or air-staged combustion and SCR	# 40
Industrial waste incineration		
Grate furnace, rotary kiln, fluidized bed combustion	Flue gas recirculation or air-staged combustion and SNCR	# 140
	Flue gas recirculation or air-staged combustion and SCR	# 70
Incineration of sludges from waste-water treatment		
Rotary kiln, fluidized bed combustion, multiple hearth furnace	Flue gas recirculation or air-staged combustion and SNCR	# 140
	Flue gas recirculation or air-staged combustion and SCR	# 70
All fuels: 11% excess O_2. Values apply to different raw gas concentrations.		

Endnote

1/ Recovery and recycling are to be understood in the broad sense, including reutilization off-site.

2/ For retrofit only.

3/ For combustion turbines.

ADDITIONAL PROPOSALS BY THE NETHERLANDS

Table 6:
Primary measures should be taken into account as well.

Table 7:
The value given for sinter plants does not require SCR.

Table 8:

Table 8: Emission sources and selected NO_x control measures with their respective reduction efficiencies and clean gas concentrations in cement production

Emission source	Combination of control measures	Clean gas concentration (mg/Nm^3)
Dry process with preheater/precalciner		
Fuel: coal	Low NO_x burner	600 – 1,000
		400 - 600
	Low NO_x burner and and SNCR	300 - 500
	Low NO_x burner and SCR	100 - 200
Solid fuels: 10% excess O_2. Values apply to different raw gas concentrations.		