

Convention on Long-Range Transboundary Air Pollution

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**Guidance document on control techniques for emissions of
sulphur, NO_x, VOCs, dust from stationary sources**

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1 Introduction

The aim of this document is to provide the Parties to the Convention with guidance on identifying best abatement options, with particular reference to best available techniques (BAT) to enable them to meet the obligations of the Protocol to abate Acidification, Eutrophication, Ground Level Ozone and Particulate Matter (PM₁₀ and PM_{2.5}).

This guidance document addresses:

- The control options for NO_x emissions defined as the sum of nitrogen oxide (NO) and nitrogen dioxide (NO₂) expressed as NO₂,
- The control options of oxidized sulphur emissions considered as the sum of sulphur dioxide (SO₂) and sulphur trioxide (SO₃), expressed as SO₂.
- The control options of VOC emissions considered as all organic compounds of an anthropogenic nature, other than methane, that are capable of producing photochemical oxidant by reaction with nitrogen oxides in the presence of sunlight.
- The control options of PM₁₀ and PM_{2.5} whose definitions are as follows:
 - PM_{2.5} : the mass of particulate matter that is measured after passing through a size-selective inlet with a 50 % efficiency cut-off at 2.5 µm aerodynamic diameter;
 - PM₁₀: The mass of particulate matter that is measured after passing through a size-selective inlet with a 50 % efficiency cut-off at 10 µm aerodynamic diameter;
 - TSP: the mass of particles, of any shape, structure or density, dispersed in the gas phase at the sampling point conditions which may be collected by filtration under specified conditions after representative sampling of the gas to be analyzed, and which remain upstream of the filter and on the filter after drying under specified conditions.

In the context of this Protocol, dust and TSP have the same meaning. As can be seen from chapter 6 abatement techniques for dust in general provide also a high removal efficiency for PM_{2.5} and PM₁₀.

As monitoring data for specific fractions of particulate matter such as PM_{2.5} and PM₁₀ are in general not available, emission levels are defined for dust.

The expression "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 the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole:

(a) "techniques" includes both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned,

(b) "available" techniques means those 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 Member State in question, as long as they are reasonably accessible to the operator,

(c) "best" means most effective in achieving a high general level of protection of the environment as a whole.

Criteria for determining BAT are as follows:

1. The use of low-waste technology;
2. The use of less hazardous substances;
3. The furthering of recovery and recycling of substances generated and used in the process and of waste, where appropriate;
4. Comparable processes, facilities or methods of operation which have been tried with success on an industrial scale;
5. Technological advances and changes in scientific knowledge and understanding;
6. The nature, effects and volume of the emissions concerned;
7. The commissioning dates for new or existing installations;
8. The length of time needed to introduce the best available technique;

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9. The consumption and nature of raw materials (including water) used in the process and energy efficiency;
10. The need to prevent or reduce to a minimum the overall impact of the emissions on the environment and the risks to it;
11. The need to prevent accidents and to minimize the consequences for the environment;
12. Information published by national and international organisations.

This guidance document presents BAT Associated Emission Levels (AELs) which can be described as follows:

- BAT AELs are levels that an operator can expect to achieve when using the BAT, and are appropriate reference points to assist in the determination of permit conditions,
- BAT AELs represent average emission levels achievable during a substantial period of time in normal operating and/or design conditions (well-proven technology),
- BAT AELs are neither emission nor consumption limit values.

BAT AELs are based on normal operating conditions and may vary with changing input materials or for varying outputs.

The BAT-AELs are based on a range of averaging periods and represent a typical load situation. Therefore, when taking account of BAT-AELs in the context of ELV setting, proper regard must always be given to the reference period to which the described BAT-AEL pertains. For peak load, start up and shut down periods, as well as for operational problems of the flue gas cleaning systems, short-term peak values, which could be higher, have to be regarded.

Where a level is described as "achievable" using a particular technique or combination of techniques, this should be understood to mean that the level may be expected to be achieved over a substantial period of time in a well maintained and operated installation or process using those techniques.

Unless otherwise indicated, the reduction measures listed are considered, on the basis of operational experience of several years in most cases, to be the most well-established and economically feasible best available techniques. BAT Associated Emission Levels are generally expressed in mg/m³ (dry gas, 273.15K and 101.325 kPa except is stipulated different) as daily average. For organic solvent uses they can be expressed in % of solvents used (solvents purchased + solvents internally recycled). The continuously expanding experience with low-emission measures and technologies at new plants as well as with the retrofitting of existing plants will necessitate regular review of this document.

Although in this guidance document, a number of measures and technologies are listed, spanning a wide range of costs and efficiencies, it cannot be considered as an exhaustive statement of control options. Moreover, the choice of control measures and technologies for any particular case will depend on a number of factors, including current legislation and regulatory provisions and, in particular, control technology requirements, primary energy patterns, industrial infrastructure, economic circumstances and specific in-plant conditions.

This guidance document provides options and techniques, along with their performance assessment for emission prevention and reduction of Sulphur, NO_x, VOCs, dust. However, the reduction of a given pollutant cannot be considered without taking into account the risk of generating other pollutants and/or increasing energy consumption. It is worthwhile to consider them together along with such other pollutant-specific control options in order to maximize the abatement effect and minimize the impact on the environment. Respective co-benefit/trade-off between different pollutants have to be carefully accounted for. This is particularly important for multi-pollutant/multi-effect approach where positive/negative effects on the reduction of Greenhouse Gases (GHGs) are possible.

This guidance document provides options and techniques, along with their performance assessment for emission prevention and reduction of Sulphur, NO_x, VOCs, dust. Performance and costs are

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documented in a series of documents elaborated by EGTEI, in the draft background document submitted to the UNECE Task Force on Heavy Metals (TFHM) of 2006, the EU Commission with the different Best Available Reference documents (BREF) and other recent publications, US EPA reports and a series of documents acknowledged nationally or internationally.

This guidance document covers the stationary sources emitting Sulphur, NO_x, VOCs and/or dust listed in table 1. Other sources are not covered by this document but may be important for some countries.

Table 1: stationary sources for emissions of sulphur, NO_x, VOCs, dust covered in this guidance document

		SO ₂	NO _x	Dust	VOCs
7-1	Combustion installation < 1MW with domestic combustion installation included	Y	Y	Y	Y
7-2	Combustion installations from 1 to 50 MW (a) Boilers (b) Gas turbines	Y	Y	Y	Y
7-3	Combustion installations > 50 MW (a) Boilers (b) Gas turbines	Y	Y	Y	Y
7-4	Mineral oil and gas refineries Combustion and furnaces (processes heaters, FCC, TCC)	Y	Y	Y	
7-5	Mineral oil and gas refineries Processes and sources of NMVOC				Y
7-6	Coke oven furnaces	Y	Y	Y	Y
7-7	Iron and steel production (iron and steel making in integrated steelworks (sinter plants, pelletization plants, blast furnaces and basic oxygen furnaces including continuous and ingot casting) and electric arc furnace steelmaking)	Y	Y	Y	Y
7-8	Ferrous metals processing iron foundries with a capacity exceeding 20 tonnes/day, as well as installations for "hot and cold forming", including hot rolling, cold rolling, wire drawing, installations for "continuous coating", including hot dip coating and coating of wire, and installations for "batch galvanizing"	Y	Y	Y	Y
7-9	Non ferrous metal processing industry (primary and secondary Al production, primary and secondary Pb production, primary and secondary Zn production and primary and secondary Cu production)	Y	Y	Y	
7-10	Cement production	Y	Y	Y	
7-11	Lime production	Y	Y	Y	
7-12	Glass production	Y	Y	Y	
7-13	Man-made fibre production	Y	Y	Y	Y
7-14	Ceramics manufacturing industry	Y	Y	Y	
7-15	Paper pulp production	Y	Y	Y	
7-16	Nitric acid production	Y	Y	Y	
7-17	Sulphuric acid production	Y	Y	Y	
7-18	Waste incineration (domestic and industrial waste, waste water treatment sludge incineration)	Y	Y	Y	
7-19	Industrial wood processing			Y	
7-20	Offshore activities (petrol)				Y
7-21	Petrol distribution – from the mineral oil refinery dispatch stations (petrol) to service stations including transport and depots (petrol)				Y
7-22	Storage and handling of organic compounds (except petrol covered by chapters 7.5 and 7.21)				Y

Table 1: stationary sources for emissions of sulphur, NO_x, VOCs, dust covered in this guidance document

		SO ₂	NO _x	Dust	VOCs
7-23	Production of organic chemicals (excluding fine organic chemical production)				Y
7-24	Production of organic fine chemicals				Y
7-25	Adhesive coating (including footwear manufacture) General coating, shoe industry, lamination				Y
7-26	Coating processes 1 Manufacture of cars Manufacture of truck cabins, trucks Manufacture of buses and trailers				Y
7-27	Coating processes 2 Winding wire coating				Y
7-28	Coating processes 3 Coil coating				Y
7-29	Other coating processes 4 Other industrial coating				Y
7-30	Solvent content in products 1: Domestic and architectural paints				Y
7-31	Manufacturing of coatings, varnishes, inks and adhesives				Y
7-32	Printing processes (Packaging printing, cold set offset heat set offset, publication sector, screen printing)				Y
7-33	Rubber processing				Y
7-34	Dry cleaning				Y
7-35	Metal degreasing				Y
7-36	Vegetable oil and animal fat extraction and vegetable oil refining				Y
7-37	Vehicle refinishing				Y
7-38	Wood impregnation				Y
7-39	Solvent content in products 2: Domestic uses of solvent (other than paints)				Y
7-40	Beer production				Y
7-41	Titanium dioxide production	Y	Y	Y	
7-42	New stationary gas and diesel engines		Y		

Acronyms used

The following acronyms are used throughout the guidance document:

BAT	Best available techniques
BREF	Best available technique reference document
ELV	Emission limit value
ESP	Electrostatic precipitator
FF	Fabric Filter
FGD	Flue gas desulphurization
TSP	Total Suspended Particles
Dust	Used in the same way as TSP
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
VOCs	In the context of the Gothenburg Protocol, all organic compounds of an anthropogenic nature, other than methane, that are capable of producing photochemical oxidant by reaction with nitrogen oxides in the presence of sunlight

2 Common general issues for the 4 pollutants

2.1 Monitoring and reporting

Several monitoring systems, using both continuous and discontinuous measurement methods, are available. However, quality requirements vary. Measurements are to be carried out by qualified institutes using measuring and monitoring systems that meet international standards. To this end, a certification system can provide the best assurance.

In the framework of modern automated monitoring systems and process control equipment, reporting does not create a problem. The collection of data for further use is a state-of-the-art technique. However, data to be reported to competent authorities differ from case to case. To obtain better comparability, data sets and prescribing regulations should be harmonized. Harmonization is also desirable for quality assurance of measuring and monitoring systems. This should be taken into account when comparing data.

To prevent discrepancies and inconsistencies, key issues and parameters, including the following, must be well defined:

- Definition of standards expressed as ppmv, mg/Nm³, g/GJ, kg/h or kg/Mg of product. Most of these units need to be calculated and need specification in terms of gas temperature, humidity, pressure, oxygen content or heat input value;
- Definition of the period over which standards are to be averaged, expressed as hours, months or a year, and of the measuring method;
- Definition of failure times and corresponding emergency regulations regarding bypass of monitoring systems or shutdown of the installation;
- Definition of methods for backfilling data missed or lost as a result of equipment failure;
- Definition of the parameter set to be measured. Depending on the type of industrial process, the necessary information may differ. This also involves the location of the measurement point within the system.

Quality control of measurements has to be ensured.

2.2 Energy management, energy efficiency, energy mix

The major part of the sulphur, NO_x and dust emissions from stationary installations result from fuel combustion to produce heat and power. Reducing fuel combustion via an efficient and rational use of

energy (energy management) may be therefore an efficient measure to reduce these air emissions but also the emissions of other pollutants and of greenhouse gases. Energy management may also contribute to increasing security of energy supply and a reduced consumption of natural resources. On the level of stationary installations but also on the level of production sites energy management means to increase overall energy efficiency by a number of different measures which can be realized alone or at best in combination like:

- implementation of an energy efficiency management system (ENEMS)
- establishment of a systems view for energy efficiency
- benchmarking
- energy efficient design (EED)
- process integration
- expertise and know-how gains on energy efficiency
- effective control, maintenance and monitoring of installations

BAT is the optimization of the combustion and steam systems but also the systems for compressed air, pumping, heating, cooling, ventilation, lighting, and other physical and chemical processes using a large number of techniques. Of particular importance are also heat recovery and cogeneration if reasonable [from [1]].

Besides energy management which focuses more on the demand side, the supply side for energy has also a large impact on air emissions. Besides fuel switch where one (fossil) fuel is replaced by another also a change in the energy mix should be considered taking into account country specific conditions such as infrastructure, energy policy and availability of resources of fossil fuels and renewable energy like wind power, solar energy, geothermal energy or biomass. Burning more biomass, especially in stoves, may, however, also lead to increasing air emissions.

Reference used for this chapter:

[1] European Commission (2008): Reference Document on Best Available Techniques, Energy Efficiency]

3 General issues for sulphur

3.1 General issues

In order to reduce SO_x emissions from combustion processes or other sources, different types of measures are applied. The main applied techniques: energy efficiency improvement, fuel switching, fuel cleaning, primary and secondary measures are presented in this chapter.

SO₂ is a major contributor to acidification, via the formation in the atmosphere, of sulphate and sulphuric acid. SO₂ residence time in atmosphere depends on meteorological conditions. The average residence time is about 3 to 5 days, hence SO₂ can be transported over hundred kilometres.

To achieve the most efficient SO_x emission reduction, beyond energy management measures, a combination of measures should be considered.

3.2 Sulphur content of fuels

Sulphur present in fuels reacts with oxygen contained in combustion air to form SO₂. Therefore SO₂ emissions arising from combustion are directly related to the sulphur content of fuels used. SO₃ is produced by oxidation of SO₂, during combustion.

Sulphur content of solid fossil fuels ranges from 0.5 % to more than 5 %. Solid fossil fuels are the largest sources of SO₂ [1]. Sulphur content of natural gas is very low as well as sulphur content of

wood. Sulphur content of liquid fossil fuels ranges from 0.001 % to more than 5 %. The availability of low sulphur content liquid fossil fuels requires the removal of sulphur at the refinery and the adoption of specific processes.

During the last decade, national and European legislation have toughened the limits required for the sulphur content of petroleum products. The table 2 presents the typical limit values applied for liquid fuels in the EU [2].

Table 2: typical limit values applied for liquid fuels in the EU

Fuel	Current sulphur content (% weight)	EU directive
Residual oil	< 1 % or 10000 ppm	1999/32/EC
Gas-oil	< 0.1 % or 1000 ppm	1999/32/EC

3.3 Fuel switching

Fuel switching (e.g. from high- to low-sulphur coals and/or liquid fuels, or from coal or liquid fuel to gas) leads to lower sulphur emissions, but there may be certain restrictions, such as the availability of low-sulphur fuels and the adaptability of existing combustion systems to different fuels. In many UE countries, some coal or oil combustion plant is being replaced by gas-fired combustion plant. Dual-fuel plant may facilitate fuel switching. Fuel switching can also have beneficial effects on nitrogen dioxide or particulate matter emission levels.

3.4 Fuel cleaning

Cleaning of natural gas is state-of-the-art technology and widely applied for operational reasons. Cleaning of process gas (acid refinery gas, coke oven gas, biogas, etc.) is also state-of-the-art technology. Desulphurization of liquid fuels (light and medium fractions) is state-of-the-art technology. Desulphurization of heavy fractions is technically feasible; nevertheless, the crude oil properties should be kept in mind. Desulphurization of atmospheric residue (bottom products from atmospheric crude distillation units) for the production of low-sulphur fuel oil is not, however, commonly practised; processing low-sulphur crude is usually preferable. Hydro-cracking and full conversion technology has matured and combine high sulphur retention with improved yield of light products. The number of full conversion refineries is constantly rising. Such refineries typically recover 80 to 90% of the sulphur intake and convert all residues into light products or other marketable products. This type of refinery consumes more energy and requires higher investments. Sulphur content of refinery products needs to correspond to the restricted value ordered by the EU and provided in table 2. Current technologies to clean hard coal can remove approximately 50% of the inorganic sulphur (depending on coal properties) but none of the organic sulphur. More effective technologies are being developed. However, they require higher specific investments. Thus the efficiency of sulphur removal by coal cleaning is limited compared to flue gas desulphurization. There may be a country-specific optimization potential for the best combination of fuel cleaning and flue gas cleaning.

3.5 Combustion Technologies

Advanced combustion technologies may improve thermal efficiency and reduce sulphur emissions. These technologies include fluidized-bed combustion (FBC), integrated gasification combined-cycle (IGCC); and combined-cycle gas turbines (CCGT). Stationary combustion turbines can be integrated into combustion systems in existing conventional power plant. This can increase overall efficiency by 5 to 7%, leading, for example, to a significant reduction in SO₂ emissions. However, major alterations to the existing furnace system become necessary. Reciprocating engines can also increase the electrical efficiency by taking advantage of the sensible heat of the exhaust gases generated by e.g. use of a feed-water combined cycle.

In FBC, the combustion takes place through a particulate bed, which can be fixed (FFBC), pressurized (PFBC), circulating (CFBC) or bubbling (BFBC). Fluidized-bed combustion is a combustion technology for burning hard coal and brown coal, but it can also burn other solid fuels, such as petroleum coke, and low-grade fuels, such as waste, peat and wood. Emissions can be further reduced by integrated combustion control in the system due to the addition of lime/limestone to the bed material. The use and/or disposal of by-products from this process may cause problems and further development is required.

The IGCC process includes coal gasification and combined-cycle power generation in a gas and steam turbine. The gasified coal is burnt in the combustion chamber of the gas turbine. Sulphur emission control is achieved by using state-of-the-art technology for raw gas cleaning facilities upstream of the gas turbine. The technology also exists for heavy oil residues and bitumen emulsions.

Combustion modifications comparable to the measures used for NO_x emission control do not exist, as during combustion the organically and/or inorganically bound sulphur is almost completely oxidized. A certain percentage, depending on the fuel properties and combustion technology, is retained in the ash. The amount of sulphur retained in ash, can be influenced by added sorbents (e.g. lime/limestone) and combustion conditions (e.g. temperature). In this guidance document dry additive processes for conventional boilers are considered as process modifications due to the injection of an agent into the combustion unit. However, experience has shown that, when applying these processes, thermal capacity is lowered, and the Ca/S ratio is relatively high and sulphur removal low. In recent years, the performance of these processes has nevertheless been optimized to the point that SO₂ removal efficiency reached 50 - 80%. Problems with the further use of the by-product have to be considered.

3.6 Secondary measures - Flue gas desulphurisation processes

These processes aim at removing already formed sulphur oxides, and are considered as secondary measures. Sulphur removal using wet, dry or semi-dry processes are used to treat the flue gases. Sulphur can also be removed using the recovery of sulphur dioxide from the flue gases. It is then either extracted (regenerative process) or converted into sulphuric acid (sulphuric acid plant). Flue gas scrubbing using water or seawater is another available technology to reduce SO₂ emissions.

In wet scrubbing technologies, the flue gas is first dedusted then cleaned by an atomized solution of alkaline compounds. SO₂ reacts with these alkaline compounds to form by products, whose chemical nature depends on the alkaline compound used. In the case of use CaCO₃ or CaO, by products may be upgraded as gypsum if some technical conditions are achieved. By products can also be upgraded using other scrubbing agent. With wet FGD, excellent efficiency can be achieved with a near-stoichiometry Ca/S ratio. This process is mainly used for reducing SO₂ emissions from coal power plants.

In dry technologies, lime or limestone is injected in solid form in the flue gases; it reacts with SO₂ to form sulphites and sulphates, which need then to be filtered in order to reduce dust emissions. The process efficiency is lower than with wet FGD and depends on several parameters such as temperature, SO₂ content of the flue gas, Ca/S ratio and residence time.

The semi-dry process is similar and also produces a solid residue. It uses moisturised lime or limestone containing about 10% of water to enhance the contact.

In regenerative processes, a regenerating agent is used to recover SO₂. Sodium sulphite can be used. It reacts with SO₂ to form sodium bisulphite, which is then evaporated to crystallise sodium sulphite and recover SO₂. A recovery rate of more than 95% can be achieved. This type of process is commonly used in titanium dioxide production plants.

In sulphuric acid production, SO₂ is first oxidised to SO₃ which is absorbed to form sulphuric acid. The sulphuric acid production process can include a single absorption stage or a double one depending on the conversion rate to be achieved. Double absorption sulphuric acid plant is more effective.

Flue gas desulphurisation is a high capital cost process best suited to high load factor plant.

The following table presents general results for several flue gas desulphurisation processes.

Table 3: general description and performance for selected flue gas desulphurisation processes [3]

	Wet scrubbing	Dry scrubbing	Regenerative process	Acid sulphuric plant (double absorption)
Efficiency	Desulphurisation rate of 95 % (exceptionally 98%) for a Ca/S ratio of 1.05	Desulphurisation rate of 60 % to 80% depending on the Ca/S ratio	Recovery rate of 95-98 %	Conversion rate of > 99%
By-product	Gypsum can be obtained under certain conditions and can be suitable for use in cement production	Calcium sulphite and sulphate not recoverable		
Limits	Possible problem of scaling	Not cost effective, large amount of waste to be treated accordingly		Dust concentration < 30 mg/Nm ³ O ₂ concentrations 5 times higher than SO ₂ concentrations.

To achieve the most efficient process for sulphur emission reductions beyond the energy management measures listed above, a combination of technological options identified in the paragraphs above should be considered. In some cases, options for reducing sulphur emissions may also reduce emissions of NO_x and other pollutants.

3.7 Costs of reduction techniques of SO₂

Costs are an important issue when selecting SO₂ emission reduction techniques. The following expenses may be relevant:

- imputed depreciation allowance and imputed interest,
- labour costs,
- expenses for auxiliary and operating materials,
- energy costs,
- maintenance and repair costs, expenditure on monitoring, expenses for external services,
- taxes, environmental levies (e.g. charges for waste water), fees, public charges.

Costs increase in general less than the capacity of the reduction technique so that larger units are often more cost-effective or unit with higher flue gas sulphur content. Dry additive processes are less cost effective for high sulphur content fuels compared to wet scrubbing processes.

Costs of SO₂ abatement techniques are developed in chapter 7.

3.8 By products and side effects

Side effects of emission abatement options/techniques can be positive or negative and should be accounted for.

Options that lead to usable by-products should be selected, as should options that lead to increased thermal efficiency and reduced waste whenever possible. Although most by-products such as gypsum,

ammonia salts, sulphuric acid or sulphur, are usable or recyclable products, factors such as market conditions and quality standards need to be taken into account.

Side effects can generally be limited by properly designing and operating the facilities. Side effects include

- impacts on energy consumption and hence greenhouse gas emissions,
- impacts on other air pollutants,
- impacts on the use of natural resources such as limestone,
- cross-media effects, e.g. on waste or water.

More particularly, the following table presents positive and negative side effects for selected flue gas desulphurisation processes.

Table 4: positive and negative side effects for selected flue gas desulphurisation processes.

Abatement technique	Positive side effect	Negative side effect
Dry scrubbers or additive injection process	Reduction of dust and heavy metals	Calcium sulphite and sulphate not recoverable Large amount of waste produced
Wet scrubbers	Reduction of dust and heavy metals Possible upgrade of by-products to gypsum	Water consumption Energy consumption Limestone consumption Waste generation

3.9 References used in chapter 3

[1] DGEMP, direction générale de l'énergie et des matières premières,
<http://www.industrie.gouv.fr/energie/>,

[2] European directive 1999/32/ EC, UEOJ 26th April 1999.

[3] Techniques de désulphurisation des procédés industriels, ADEME, 1999.

4 General issues for NO_x

4.1 General issues

The generic term NO_x refers to the sum of nitrogen oxide (NO) and nitrogen dioxide (NO₂), expressed as NO₂. Nitrous oxide (N₂O), a greenhouse gas, is not covered in NO_x. The main source for NO_x is combustion where primarily NO is formed [1]. NO is then rapidly converted to NO₂.

NO_x emissions contribute to acidification via formation of nitrous acid (HNO₂) and nitric acid (HNO₃), to eutrophication, to tropospheric ozone formation and (in particular NO₂) to irritation and damage to respiratory organs. Furthermore, NO_x may react with ammonia to form secondary fine particles with negative health effects.

In combustion, three main types of NO_x formation are distinguished:

- **Thermal NO_x**: molecular nitrogen (N₂) from air and molecular oxygen (O₂) dissociate at high temperature and react to form NO_x. The reaction is reversible and usually becomes significant at temperatures above around 1300 °C [1]. NO_x formation increases with temperature and residence time.
- **Fuel NO_x**: in fuel NO_x, the nitrogen source for NO_x formation is the fuel itself. Two path ways may be distinguished: i) during initial combustion, volatiles including oxidized nitrogen are

released and ii) during later stages when the char is oxidized and the nitrogen contained in the char is oxidized to NO_x. Fuel NO_x formation is significant at temperatures above about 800°C. The amount of fuel NO_x depends on the N content of fuels and on combustion conditions.

- **Prompt NO_x:** fuel radicals react with molecular nitrogen (N₂) from the air to form NO_x. Compared to thermal and fuel NO_x, prompt NO_x is of lesser importance for the sources considered here.

In order to reduce NO_x formation and NO_x emissions from combustion processes different types of measures like energy efficiency improvements (cf. Chapter 2), fuel switch as well as primary and secondary measures are applied. To achieve the most efficient NO_x reduction, beyond energy management measures, a combination of measures should be considered. To identify the best combination of measures, a site-specific evaluation is needed.

4.2 Fuel switching

Switching to low NO_x producing fuels is one option to reduce NO_x emissions but is governed by country specific conditions such as infrastructure and energy policy. Fuels with high nitrogen content like heavy fuel oil and coal may lead to high fuel NO_x formation and hydrogen rich fuels like natural gas as a result of high combustion temperatures to high thermal NO_x formation. The choice of the fuel may also have effects on other emissions like sulphur, particulate matter and greenhouse gas emissions as well as on applicability and need of abatement measures.

4.3 Fuel cleaning

Fuel cleaning to remove nitrogen is not a commercial option. Hydroprocessing in refineries, however, also reduces the nitrogen content of end products.

4.4 Primary measures

Primary measures reduce NO_x generation at the source by a number of different principles or methods or a combination of them [1]:

- Reducing peak temperature,
- Reducing residence time at peak temperature,
- Chemical reduction of NO_x during combustion process,
- Reducing nitrogen in the combustion process.

In the following paragraphs, an overview on available primary measures is given. Their applicability depends on the industrial sector and the production process.

Reducing peak temperature: As thermal NO_x formation depends largely on the combustion temperature, a reduction in temperature is one option to reduce NO_x formation. Reducing peak temperature can be achieved by the following methods i) diluting the heat produced during the combustion process, ii) cooling down, and iii) reducing the oxygen available for combustion [1] but also by applying other combustion techniques like fluidized bed combustion (FBC) which operates at lower temperatures and includes an inherent air-staging. Main methods for reducing peak temperature are:

- Substoichiometric combustion, i.e. using a fuel-rich mixture so that oxygen is a limiting factor (fuel acts also as reducing agent),
- Suprastoichiometric combustion, i.e. using a fuel-lean mixture to dilute combustion heat,
- Injecting cooled oxygen-depleted fuel gas to dilute combustion heat,
- Injecting cooled oxygen-depleted fuel gas with added fuel to dilute combustion heat, to reduce the reaction temperature and to make oxygen a limiting factor,
- Injecting water or steam to dilute combustion heat and to reduce the reaction temperature.

Reducing residence time at peak temperature: As thermal NO_x formation depends largely on the time the fuel gas remains in the high temperature region, reducing this residence time reduces also NO_x formation. Methods to reduce residence time include [1]:

- Injection of fuel, steam, re-circulated flue gas or combustion air immediately after combustion,
- Reducing the extension of the high temperature zone which can be faster left by the flue gas then.

Chemical reduction of NO_x during combustion process: NO_x can be reduced to N₂ using a reducing agent which is itself oxidized. The principle of chemical reduction is widely used in secondary measures but can be also used as a primary measure when reduction takes already place during the combustion process. Main methods are:

- Substoichiometric combustion, i.e. in a fuel rich mixture so that the remaining fuel may act as reducing agent,
- Re-burning of the flue gas with fuel added (with the added fuel acting as a reducing agent),
- Generation of fuel-lean and fuel-rich conditions in the combustion zone.

Reducing nitrogen in the combustion process: Reducing NO_x formation by reducing the available nitrogen can be achieved using nitrogen poor fuels like natural gas (see fuel switch) as well as by using oxygen instead of air for the combustion process.

The following primary measures which are based on the principles and methods described above are mainly in use, each with its specific advantages and disadvantages, cf. e.g [1], [11]. Some of the primary measures are typical for retrofit, others for new installations and others are only applicable in new installations.

- **Low excess air combustion (LEA):** In order to ensure complete combustion air is often added in large excess which may result in higher thermal NO_x formation when air nitrogen is oxidized [2], [3], [4]. Reducing the excess air reduces also NO_x formation.
- **Flue gas recirculation (FGR):** Re-circulating cooled flue gas reduces the combustion temperature in a secondary combustion stage and also oxygen concentration so that thermal NO_x formation is reduced. Heat of the flue gas may be recovered in a heat exchanger [1], [5].
- **Air staging (AS):** The principle of air staging is to create two zones, one fuel-rich zone where initial combustion takes place and a second one where air is added to ensure complete combustion. This allows reducing thermal NO_x formation in the first zone where less nitrogen is available and in the second where temperature is lower. The zone may be created in different ways. In **Biased Burner Firing (BBF)** air and fuel flow rates are varied, in **Burners Out of Service (BOOS)** the fuel flow to the burner is cut for a short time and in **Overfire Air (OFA)** air is injected above the normal combustion zone [3], [4], [5]. Staged air combustion is frequently used in conjunction with Low NO_x burners (LNB).
- **Fuel staging (FS):** Fuel staging is similar to air staging but with fuel instead of air. The first stage is extremely fuel-lean which reduces the temperature. Fuel added in the second stage acts as a reducing agent for formed NO_x. In a third stage air is added to ensure burnout [6].
- **Fuel re-burning (FR):** Fuel re-burning is similar to flue gas recirculation (FGR) but with added fuel in the flue gas leading to lower temperatures. If added in a second combustion stage fuel re-burning makes use of the fuel as reducing agent and is similar to fuel staging (FS).
- **Reduced air preheat (RAP):** Combustion air is in general preheated by the flue gases to cool them down in order to improve efficiency. Reducing this preheating reduces also flame temperature and hence NO_x formation but also overall energy efficiency [1], [3].
- **Low NO_x burners (LNB):** Low NO_x burners mix fuel and air/flue gas in a way so that different zones are created as in staged combustion. The zoning allows lower flame temperature and oxygen concentration as well as chemical reduction of NO_x by fuel in some of the zones [1], [5]. Low NO_x burners can be further differentiated into air-staged LNB, flue-gas recirculation LNB and fuel-staged LNB depending on the principle used for reducing NO_x emissions. A further development is the Ultra low NO_x burner.
- **Water/steam injection:** Water and steam are injected to cool the flame and to reduce thermal NO_x formation.

- **Oxycombustion:** In oxycombustion the combustion air is replaced by oxygen so that no thermal NO_x is produced. So far oxycombustion is to a larger extent only applied for glass production but its use might become more emerging in future as oxycombustion is one option to achieve high CO₂ concentrations in flue gas which is an advantage for CO₂ capture and sequestration [7].
- **Combustion optimization:** In combustion optimization the combustion process is actively controlled, e.g. by making use of specialised software. One option is to slightly decrease combustion efficiency in order to reduce NO_x emissions [1].
- **Catalytic combustion:** Using a catalyst to reduce combustion temperature below NO_x formation temperature may reduce NO_x emissions very strongly. However, applications are still rare in practice [1] though gas turbines seem to be an interesting field of application [8].

The techniques reported in § 4.4 are an inventory of available technologies to reduce NO_x emissions, which does not mean that those reported technologies are applicable to each industrial sector or process of production.

For stationary gas and diesel engine measures refer to document 7-42.

4.5 Secondary measures

Secondary measures (add-on or end of pipe technologies) reduce the emissions of already formed NO_x to the environment.

There are two main principles:

- chemical reduction of NO_x by a reducing agent with or without a catalyst,
- sorption/neutralisation of NO_x.

The following secondary measures are mainly in use, each with its specific advantages and disadvantages [1]:

- **Selective Catalytic Reduction (SCR):** In SCR, NO_x is reduced to N₂ by a reducing agent (usually ammonia) which is directly injected into the flue gas over a catalyst in the presence of sufficient oxygen. NO_x-conversion takes place on the catalyst surface at a temperature between 170 and 510 degree C (with a range between 300 and 400 degree C being more typical, the minimum flue gas temperature is dependent on the sulphur content of the fuel. At a too low flue gas temperature ammonium bisulphate is formed which will clog the SCR elements. A limitation for the applicability of SCR [11] exists for diesel and two stroke engines which need to be operated with often varying loads. These units are operated frequently on isolated systems to be operated for a reduced number of hours only. According to the electricity demand, these engines need to be started up and shut down several times a day. SCR is an applied technique for diesel engines, but cannot be seen as BAT for engines with frequent load variation, including frequent start up and shut down periods due to technical constraints. A SCR unit would not function effectively when the operating conditions and the consequent catalyst temperature are fluctuating frequently outside the necessary effective temperature window. As a result, SCR is part of BAT, but no specific emission levels are associated with BAT in a general sense.
- **Selective Non-Catalytic Reduction (SNCR):** Similar to SCR a reducing agent (usually ammonia, urea or caustic ammonia) is used to reduce NO_x but in contrast to SCR, without a catalyst and at a higher temperature between 850 and 1100°C.

Other secondary NO_x control techniques include:

- **NOXSO Process:** The NOXSO process is based on simultaneous adsorption of SO₂ and NO_x from flue gas by a regenerable sorbent, finally leading to liquid SO₂, N₂ and O₂. Claimed efficiencies are 98% for SO₂ and 75% for NO_x [9].
- **SO_x-NO_x-Rox-Box (SNRB):** SNRB uses a catalytic baghouse for integrated removal of SO_x (via injection of alkali sorbent), NO_x (via ammonia injection and SCR), and dust (cf 10). Problems with this technique include the production of hazardous waste as by-product and rather low abatement efficiencies.
- **Limestone Injection Multistage Burner (LIMB):** LIMB shows lower reliability and rather low NO_x abatement efficiencies.

In integrated gasification combined cycle (IGCC) the fuel is gasified under reducing conditions to syngas. The syngas is then cleaned and burnt in either air or oxygen. This enables to achieve very low NO_x emission levels. IGCC is seen as one of several key technologies in the framework of carbon capture and storage (CCS). So far its application is restricted to few, mostly demonstration plants. With CCS, IGCC could become commercially available around 2020.

The selection of the most suitable measure depends on many factors related to e.g. [11]:

- fuels used,
- combustion technology applied,
- operational mode of installation,
- process characteristics in industrial processes,
- new installation or retrofitting,
- flue gas characteristics (NO_x concentration, temperature, humidity, dust, other pollutants, catalyst poisons etc.),
- flow rate of flue gas,
- emission levels to be achieved,
- side and cross media effects,
- operational safety and reliability,
- costs.

The following table gives a brief overview about the performance of primary and secondary measures for reducing NO_x emissions in large combustion plants; cf. the sectoral chapters for more detailed information on sector specific issues.

Table 5: average reduction efficiency of selected primary and secondary measures for reducing NO_x emissions in large combustion plants for boilers [11]

Technique	Average NO _x reduction rate*	Technical limitations
Low excess air (LEA)	10-44%	incomplete burn-out
Burner out of service (BOOS)	10-70%	incomplete burn-out
Biased burner firing (BBF)		
Overfire air (OFA)		
Flue gas recirculation (FGR)	< 20% (coal) 30-50% (gas, combined with OFA)	flame instability
Reduced air preheat (RAP)	20-30%	
Fuel staging (FG)	50-60%	
Air-staged LNB	25-35%	incomplete burn-out flame instability
Flue-gas recirculation LNB	<20%	flame instability
Fuel-staged LNB	50-60%	incomplete burn-out flame instability
Selective catalytic reduction (SCR)	80-95%	ammonia slip; contamination of fly ash by ammonia; air heater fouling
Selective non-catalytic reduction (SNCR)	30-50%	ammonia slip which is usually higher than with SCR
* If several measures are applied reduction rates are different.		

4.6 Costs of NO_x emission reduction techniques

Costs are an important issue when selecting NO_x emission reduction techniques. The following expenses may be relevant [12]:

- imputed depreciation allowance and imputed interest,
- labour costs,
- expenses for auxiliary and operating materials,
- energy costs,
- maintenance and repair costs, expenditure on monitoring, expenses for external services,
- taxes, environmental levies (e.g. charges for waste water), fees, public charges.

Costs increase in general less than the capacity of the reduction technique so that larger units are often more cost-effective. Retrofitting of existing installations is often possible but in general at higher costs.

For primary measures, investment related costs are in general relatively low and in new installations there are often no additional costs. But costs accruing from efficiency decreases may be significant and have to be accounted for.

For SCR, the cost of retrofitting may be high because of the difficulty of building a catalyst reactor close to the boiler. In addition, for SCR the following costs are most relevant: investment related costs, ammonia costs, electricity costs, catalyst replacement costs and labour costs. SNCR generally has lower costs than SCR as there are no costs for catalysts and catalyst reactor housings. However, costs for SCR and SNCR depend e.g. on the nature of the waste gas, its temperature and the required abatement efficiency. As a consequence, the additional costs for catalyst replacement in the case of SCR may be compensated by a significantly lower ammonia consumption compared to SNCR.

4.7 Side effects

Side effects of emission abatement options/techniques can be positive or negative and should be accounted for. Side effects can generally be reduced by properly designing and operating the facilities. Side effects include

- impacts on energy consumption and hence greenhouse gas emissions,
- impacts on other air pollutants,
- impacts on use of natural resources,
- cross-media effects, e.g. on waste or water.

More specifically, the side effects to be considered with different emission reduction techniques are:

- **Primary measures:** possible side effects are lower overall energy efficiency, increased CO and soot formation and hydrocarbon emissions, corrosion due to reducing atmosphere, increase in unburnt carbon in fly ash.
- **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 N₂O under certain process conditions. The handling of the ashes needs consideration in relation to their possible use and/or disposal.
- **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 SO₂ to SO₃ (corrosion and fouling). 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 catalyst lifetime has been improved and reprocessing options exist. Biomass and waste burning can reduce catalyst life.
- **SNCR:** side effects to be considered are ammonia in the exhaust gas, formation of ammonium salts on downstream facilities, the formation of N₂O, when urea, for instance, is used as a component of the reducing mixture, and CO releases. The ammonia slip from SNCR usually is much higher than from SCR due to the required over-stoichiometric dosage of the reducing

agent (at the high temperatures required for SNCR, part of the injected ammonia reacts to form additional NO_x).

The **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 NH₃ is still considered appropriate, even when taking into account the indirect emissions related to the production and transport of NH₃.

4.8 References used in chapter 4

- [1] US EPA (1999): Nitrogen Oxides, Why and how they are controlled? U.S. Environmental Protection Agency (EPA), Technical Bulletin EPA-456/F-99-006R.
- [2] Lim, K.J., C. Castaldini, and C.D. Wolbach (1982): A promising NO_x-Control Technology. – Environmental Progress 1, 167-177.
- [3] Wallin, S.C. (1986): Abatement systems for SO_x, NO_x, and Particles – Technical Options. – The Environmentalist 6, 111-124.
- [4] A summary of NO_x reduction technologies. – The Texas Institute for Advancement of Chemical Technology Special Report 1, 2000.
- [5] Lani, B.W., T.J. Feeley, J. Murphy, and L. Green (2005): A review of DOE/NETL's advanced NO_x control technology R&D program for coal-fired power plants. – DOE/NETL's NO_x R&D Program Review, March 2005.
- [6] Zabetta, E.C., M. Hupa and K. Saviharju (2005): Reducing NO_x emissions using fuel staging, air staging, and selective non catalytic reduction in synergy. – Ind. Eng. Chem. Res. 44, 4552-4561.
- [7] Results of work of the EGTEI expert sub-group on Emerging Technologies/Techniques. Report by the Chair of the Expert sub-group on Emerging Technologies/Techniques to the Working Group on Strategies and Review – 1 – 5 September 2008.
- [8] Cocchia, S., G. Nutinia, M.J. Spencerb and S.G. Nickola (2006): Catalytic combustion system for a 10 MW class power generation gas turbine. – Catalysis Today 117, 419-426.
- [9] Black, J.B., M.C. Woods, J.J. Friedrich, and J.P. Browning: The NOXSO clean coal project. - NOXSO Corporation, PA, USA.
- [10] Kudlac, G. A., G.A. Farthing, T. Szymanski, and R. Corbett (1992): The SO_x-NO_x-Rox BoxTM (SNRB). - Environmental Progress, 11, 33 – 38.
- [11] LCP BREF (2006): Reference Document on Best Available Techniques for Large Combustion Plants. – European Commission, 618 pp.
- [12] VDI 3800, Determination of costs for industrial environmental protection measures. Verein Deutscher Ingenieure, 2001.
- [13] EGTEI: Final background document on the sector “glass industry”, DFIU/IFARE 2003.

5 General issues for VOCs

5.1 General issues

Definitions

Volatile organic compounds or VOCs means, unless other wise specified, all organic compounds of an anthropogenic nature, **other than methane**, that are capable of producing photochemical oxidant by reaction with nitrogen oxides in the presence of sunlight.

An organic compound is any compound containing at least the element carbon and one or more of hydrogen, halogens, oxygen, sulphur, phosphorus, silicon or nitrogen, with the exception of carbon oxides and inorganic carbonates and bicarbonates [1].

On case by case, other definitions can be encountered in sectoral chapters:

For the uses of solvent considered in chapter 7-25 to 7-38 and suggested technical annex VI, volatile organic compounds (VOC) mean any organic compound as well as the fraction of creosote, having at 293.15 K, a vapour pressure of 0.01 kPa or more, or having a corresponding volatility under the particular conditions of use [9].

For the solvent content of products, chapter 7-39 and suggested technical annex XI, volatile organic compounds (VOCs) means any organic compound having an initial boiling point less than or equal to 250°C measured at a standard pressure of 101.3 kPa. This definition is compatible with the previous one, as there is a relation between the boiling point and the vapour pressure.

The leak detection and repair programme (LDAR) [3] developed by the US EPA and being subject of standardisation in Europe [4] is based on a vapour pressure of VOCs of 300 Pa at 295.15 K.

VOCs result from a larger number of sources both anthropogenic and natural:

- Thermal processes: hydrocarbons emitted from thermal processes (fixed sources and mobile sources) contribute to the total amount of VOCs,
- Use of organic solvent: an organic solvent is any VOC which is used alone or in combination with other agents, and without undergoing a chemical change, to dissolve raw materials, products or waste materials, or is used as a cleaning agent to dissolve contaminants, or as a dissolver, or as a dispersion medium, or as a viscosity adjuster, or as a surface tension adjuster, or a plasticiser, or as a preservative [1],
- Transport and handling of liquid fuels and light organic compounds (petrol as example),
- Refineries and organic chemical industries,
- Natural sources.

VOCs play a significant role in the atmospheric chemistry. VOCs, through complex photochemical reactions, contribute to the formation of toxic oxidants, such as tropospheric ozone and other oxidants, which can trigger a variety of health problems and have detrimental effects on plants and ecosystems.

Certain VOCs have been shown to be highly toxic, mutagenic and carcinogenic. These VOCs have to receive increased attention due to their implication for human health. These VOCs are those affected by the following [7]:

- H 350: may cause cancer;
- H 340: May cause genetic defects;
- H 350i: may cause cancer by inhalation;
- H 360F: May damage fertility;
- H 360D: May damage the unborn child.

These VOCs should be reduced as far as possible in priority. VOCs associated to risk phrases H351 suspected of causing cancer and/or H 341 suspected of causing genetic defects, should be also considered with attention and reduced as far as possible.

In order to reduce efficiently VOC emissions, it is of particular importance to consider both the reduction of stack emissions and fugitive emissions. Stack emissions refer to emissions of which the source and the direction of gas flow is clearly definable. They enter in the atmosphere by passing through a stack or a duct designed to direct and control their flow. Sources of fugitive emissions are not clearly defined. They enter in the atmosphere without passing through a stack or duct designed to direct or control the emissions. They include uncaptured emissions released to the outside environment via windows, doors, vents and similar openings [2]. In industrial plants, fugitive emissions have a diffuse character as they can arise from a lot of sources spatially dispersed.

Instead of applying emission limit values (ELV), e.g. connected to end-of-pipe measures, reduction schemes can be used. Solvent management plans have to be used as guidance for these reduction schemes. The purpose of a reduction scheme is to allow a plant operator to achieve emission reductions similar to those achieved if given limit values were to be applied by other means. Definitions of solvent management plan and of a reduction scheme are given below. Solvent management plan and reduction scheme are a key element of annexe VI to the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. They help to verify compliance with given regulations, identify future reduction options, and enable the provision of information on solvent consumption, emissions and compliance with regulations to the public.

In this guidance document, emission abatement options/techniques are characterised by:

- Emission factors expressed in terms of mass of emitted substance (VOCs) or mass of total organic carbon per activity within a sector (e.g. g/m² in car coating); or
- Emission factors expressed in terms of mass of emitted substance (VOCs) or mass of total organic carbon per mass of solvent input (solvent purchased + solvent recovered and reused) within a sector (e.g. % of solvent used in speciality organic chemistry); or
- Concentrations in terms of mass of emitted substance (VOCs) or total organic carbon per volume unit of the exhaust gases; or
- Abatement efficiency (%).

In general, no further subdivision for VOCs is made with regard to specific substances. Performance is reported where available.

5.2 Knowledge of emissions and solvent management plan

In order to minimise VOC emissions and construct a reduction plan, perfect knowledge of emissions is essential. This knowledge is based on monitoring VOC emissions in stacks, determining VOC fugitive emissions by several relevant techniques.

A solvent management plan is a key technique to understand the consumption, use and emissions of solvents, especially fugitive VOC emissions [5].

The solvent management plan consists in estimating solvent inputs and solvent outputs. Inputs are often easily known. On contrary, some outputs cannot be estimated easily. The solvent mass balance is a tool for estimating VOC emissions based on the following principles [1].

Definitions of inputs and outputs to be considered are as follows:

Inputs of organic solvents (I):

I1 The quantity of organic solvents or their quantity in preparations purchased which are used as input into the process in the time frame over which the mass balance is being calculated.

I2 The quantity of organic solvents or their quantity in preparations recovered and reused as solvent input into the process. (The recycled solvent is counted every time it is used to carry out the activity.)

Outputs of organic solvents (O):

O1 Emissions in waste gases.

O2 Organic solvents lost in water, if appropriate taking into account waste water treatment when calculating O5.

O3 The quantity of organic solvents which remains as contamination or residue in products output from the process.

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O4 Uncaptured emissions of organic solvents to air. This includes the general ventilation of rooms, where air is released to the outside environment via windows, doors, vents and similar openings.

O5 Organic solvents and/or organic compounds lost due to chemical or physical reactions (including for example those which are destroyed, e.g. by incineration or other waste gas or waste water treatments, or captured, e.g. by adsorption, as long as they are not counted under O6, O7 or O8).

O6 Organic solvents contained in collected waste.

O7 Organic solvents, or organic solvents contained in preparations, which are sold or are intended to be sold as a commercially valuable product.

O8 Organic solvents contained in preparations recovered for reuse but not as input into the process, as long as not counted under O7.

O9 Organic solvents released in other ways.

Determination of solvent consumption and NMVOC emissions can be done according to equations presented here after:

Consumption can be calculated according to the following equation:

$$C = I1 - O8$$

Total NMVOC emissions are defined as follows:

$$E = F + O1$$

Where F is the fugitive emission as defined below:

$$F = I1 - O1 - O5 - O6 - O7 - O8$$

or

$$F = O2 + O3 + O4 + O9$$

This quantity can be determined by direct measurement of the quantities. Alternatively, an equivalent calculation can be made by other means, for instance by using the capture efficiency of the process.

The fugitive emission value as well as the total emission can be expressed as a proportion of the input, which is calculated according to the following equation:

$$I = I1 + I2$$

The solvent management plan can be done on a regular basis such as an annual basis, in order to control progress carried out, take the necessary measures if deviations are observed and be in position to assess the compliance of the installation with regulation implementing ELVs.

5.3 General approaches to reduce VOCs emissions

For nearly all stationary sources, measures to control or to prevent VOCs emissions are available. A distinction is generally made between primary, secondary (add-on or end-of-pipe) and structural measures. Unless stated otherwise, measures are applicable to new and existing installations. The reduction of VOC emissions outside of stationary sources focuses on the restrictions in the VOC content of products.

The following list gives a general outline of available measures for reducing VOC emissions, which may also be combined with secondary measures:

- (a) More effective VOC control technologies in terms of efficient maintenance of equipment, better capture of waste gases, and generally optimized operating conditions;
- (b) Substitution of VOC, e.g. use of low-organic solvent or organic-solvent-free materials and processes, such as water-based paints, water-based degreasing, etc., and/or process modifications;
- (c) Reduction of emissions by best management practices such as good housekeeping, improved inspection and maintenance programmes, by changes in processes such as closed circuit machines, improved sealing of storage tanks, or by structural changes such as transfer of activity to locations where VOC emissions are reduced more efficiently, e.g. via pre-coating of certain products;
- (d) Recycling and/or recovery of VOCs by control technologies such as condensation, adsorption, absorption, and membrane processes (pre-processing step). A further option is the recovery of heat (energy recovery) from VOCs. Preferably, the organic compounds should be reused on-site; this can

be facilitated by the use of only few organic solvents instead of complex mixtures. Complex mixtures may be better treated off-site; however, emissions may be caused by distribution, handling, transport and storage;

(e) Destruction of VOCs by control technologies such as thermal or catalytic incineration, or biological treatment. For incineration, heat recovery is recommended in order to reduce operating costs and resource consumption. Another common procedure for destroying non-halogenated VOCs is to use VOC-laden gas streams as secondary air or fuel in existing energy-conversion units.

5.3.1 Primary measures

Possible primary measures for the control of emissions from the industrial use of organic solvents are: prevention (use of low- or no-organic solvent containing materials and processes), good housekeeping, process-integrated measures and structural measures. Thus, two approaches can in principle be used: a product-oriented approach, which, for instance, leads to a reformulation of the product (paints, inks, degreasing products, etc.); and process-oriented changes (increase of transfer efficiency, use of sealed chamber systems for degreasing...); Moreover, the product-oriented approach should be looked at, inter alia, because of the positive spin-off effects on emissions from the organic solvents manufacturing industry. Moreover, the environmental impact of emissions can be reduced by product reformulation to replace solvents by less harmful alternatives. Closed systems may lead to very low organic solvent emissions as well. There is a rapid ongoing development towards low-organic solvent or organic-solvent-free paints, which are among the most cost-effective solutions.

For the domestic use of paints and other solvent-containing products, only a product-oriented approach is possible. The same is true for the painting of constructions and buildings, the commercial use of cleaning products, etc. The use of water-based systems (e.g. for paints and adhesives) is an effective measure already used, especially for products for both commercial and domestic purposes.

5.3.2 Secondary measures

When primary measures are not sufficient to reach high VOC reductions or are not technically applicable, add-on control technologies can be applied alone or in combination. These techniques are used to reduce VOC emissions from processes and solvent uses.

The following techniques can be distinguished:

- Techniques based on destruction of VOCs present in waste gases:
 - Recuperative or regenerative thermal oxidation,
 - Catalytic recuperative or regenerative oxidation,
 - Biological destruction.
- Techniques enabling possible recovery of VOCs for possible reuse in the process after a specific treatment carried on site or by external companies:
 - Adsorption on activated carbon or zeolithe substrates,
 - Absorption in adapted scrubbing liquors (water, heavy oils),
 - Condensation and cryogenic condensation,
 - Membrane separation associated to other processes such as cryogenic condensation and adsorption.

Processes using thermal oxidation may enable valorisation of the energy content of VOCs. However, in most cases, this valorisation is difficult due to the low VOC concentrations generally encountered. Primary thermal energy recovery (for warming inlet gases as example) is indispensable but secondary thermal energy recovery is often most difficult to be implemented in existing plants. The VOCs concentrations have to be sufficient for enabling the oxidation unit to run without additional fuel consumption and to be consequently in autothermal conditions. Lower concentrations require additional fuel consumption which can be rapidly prohibitive.

Recuperative or regenerative thermal oxidation. In recuperative or regenerative oxidation, VOCs are destructed at high temperature. The oxidation temperature depends on the type of energy recovery system used. In recuperative oxidiser, a preheating thermal exchanger is used to heat inlet gases. The heat recovery ranges from 60 to 70 %. The temperature ranges from 650 to 750°C. The system can only be autothermal for high concentrations of VOCs ranging from 8 to 10 g/Nm³. The regenerative thermal oxidiser is constituted of two or three ceramic heat exchangers. Waste gases containing VOCs pass through a first ceramic exchanger. They are heated. They enter after in the combustion chamber maintained at about 800 to 900 °C by burners. Before being released into the atmosphere they leave the oxidiser through another ceramic exchanger, transferring its thermal energy to be re-used for preheating the next cycle. The role of the exchanger, heating or cooling, is inversed regularly. Heat recovery efficiency up to 95 % can be achieved. Regenerative thermal oxidisers are suitable for large waste gas flow rates and can be autothermal at VOCs concentrations from 2 to 3 g/Nm³. Output VOC concentrations lower than 20 mg/Nm³ can be achieved. Methane is largely represented in the resulting concentrations.

Recuperative or regenerative catalytic oxidation. In recuperative or regenerative catalytic oxidation, the use of a catalyst enables VOCs to be destroyed at lower temperature than in thermal oxidation. Catalysts used are either precious metals (Platinum, Palladium or rhodium) or metal oxides (Cr, Fe, Mo, Mn, Co, Cu, Ni). The principles of heat exchange are the same as in thermal oxidation. Oxidation temperatures range from 200 to 500 °C according to catalyst used and the type of heat exchanger used. Recuperative catalytic oxidiser can be autothermal at concentrations ranging from 3 to 4 g/Nm³. Regenerative catalytic oxidiser can be autothermal at concentrations ranging from 1 to 2 g/Nm³. Life time of catalysts is limited. Lifetime of metal oxide based catalysts is about 12000 h. Life time of precious metal based catalysts is about 15000 h to 25000 h. Catalysts are sensible to poisons and they can be deactivated irreversibly by certain of them. Output VOC concentrations lower than 20 mg/Nm³ can be achieved. Methane is largely represented in the resulting concentrations.

Biological destruction: biological destruction can be carried out in biofilters and in bioscrubbers. Micro organisms are able to destruct biodegradable VOCs in humid conditions and at low temperature. Warm waste gases (> 35 °C) must be cooled. In biofilter, microorganisms are maintained at the surface of a moist organic substrate which can be peat, heather or compost. In bioscrubbing, a combination of wet gas scrubbing and biodegradation is carried out. Microorganisms are suspended in the scrubbing water. In biofilters, residence time must be sufficient to enable biological reactions to occur. Accepted inlet VOC concentrations are low. Biological oxidation is used primarily for low concentrations. Output VOC concentrations from 100 to 150 mg/Nm³ can be achieved. Lower concentrations are however more difficult to obtain.

Adsorption on activated carbon or zeolithes. In adsorption, VOCs are physically bound to the surface of a media which can be activated carbon or zeolithes. The adsorption capacity of activated carbon or zeolithe is limited and consequently they must be regenerated to recover their initial capacity to adsorb VOCs and recover VOC. Several configurations exist but in most of the cases, fixed bed adsorption devices are used with 2 or 3 beds. A bed is in adsorption phase, the second one is in desorption phase. Desorption is carried at high temperature with steam or inert gas. The adsorption temperature must be below 40 °C because the effectiveness of adsorption improves at low temperature. Inlet gases must be consequently conditioned. VOCs are recovered after a special treatment which involves condensation, separation and distillation if several VOCs are present. VOCs abatement efficiency depends on a lot of parameters such as adsorption temperature, type and number of VOCs to be eliminated, frequency set point for desorption. Output VOC concentrations from 50 to 100 mg/Nm³ can be achieved. Efficiencies achieved depend on numerous factors such as correct dimensioning of the installation, the frequency of desorption and the threshold value for desorption...

Condensation and cryogenic condensation: in condensation VOCs are cooled below the stream dew point. Condensation of VOCs is carried out by chilling and /or pressurisation. Cooling media can be cooled water, chilled water, refrigerants and liquid nitrogen. Diverse heat exchangers equipment can be used. Condensation with cooled water, chilled water or refrigerants is often used as pre-treatment but is not sufficient to achieve high reduction of emissions. Output VOC concentrations from 100 to 150 mg/Nm³ can be achieved. Efficiencies achieved depend on numerous factors such as

correct dimensioning of the installation, the frequency of desorption and the threshold value for desorption...

Liquid nitrogen is used in cryogenic (temperature less than -160°C) condensation. Cryogenic condensation is a versatile process that is not VOCs specific. Typically, condensation takes place with liquid nitrogen as the refrigerant in a straightforward heat exchange process. The VOCs condense on the shell side of the exchanger then drains into a collection tank, from which it can be recycled, reclaimed, recovered for reuse or for disposal. During condensation, the presence of water vapour or VOCs with a high melting point can cause freezing on the external surface of the tubes inside a cryogenic condenser. Special configuration exists to avoid this problem and especially a series of condenser can be used with different temperature set points [8]. Cryogenic condensation is best suited to low waste gas flowrates and/or high VOCs concentrations. Output VOC concentrations from 50 to 100mg/Nm³ can be achieved. Efficiencies achieved depend on numerous factors such as correct dimensioning of the installation, the volatility of solvents...

Membrane separation: VOC emissions can be concentrated using organic selective (VOCs permeable) membranes. Air and VOCs permeate through the membrane at rates determined by their relative permeabilities and the pressure difference across the membrane. Membranes are typically 10 to 100 times more permeable to VOCs than air, depending on the specific VOC characteristics. Based on the system design, the exit membrane stream VOC concentration can be increased five to fifty times the inlet membrane stream concentration. Concentrated gas streams can be then compressed and condensed by the use of conventional condensation technology. Membrane separation cannot be used alone. Subsequent gas cleaning device is necessary.

The choice of a control technique will depend on various parameters, such as the concentration of VOCs in the raw gas, the gas volume flow, the type and composition of VOCs, and others. Therefore, some overlap in the fields of application may occur. In that case, the most appropriate technique must be selected according to case-specific conditions. An overview of the most relevant parameters for the application of some secondary measures is outlined in table 2. The overall efficiency of secondary measures in the solvent-using sectors depends to a large extent on the capturing efficiency for the VOC-laden waste gas flows. Especially for fugitive emissions, capturing is paramount for the overall efficiency of the system.

Table 6: overview of the most relevant parameters for the application of secondary measures

	Thermal recuperative oxidation	Thermal regenerative oxidation	Catalytic recuperative oxidation	Catalytic regenerative oxidation
Ranges of concentrations	Adapted to high concentrations 5 to 20 g/Nm ³	Adapted to low concentrations 2 to 10 g/Nm ³	Adapted to low concentrations 2 to 10 g/Nm ³	Adapted to very low concentrations C < 5 g/Nm ³
Waste gas flow rates	1 000 to 30 000 Nm ³ /h	10 000 to 200 000 Nm ³ /h	1 000 to 30 000 Nm ³ /h	10 000 to 100 000 Nm ³ /h
Autothermic threshold	8 to 10 g/Nm ³	2 to 3 g/Nm ³	3 to 4 g/Nm ³	1 to 2 g/Nm ³
Performances VOCs (C eq) NOX CO	< 20 mg/Nm ³ < 100 mg/Nm ³ < 100 mg/Nm ³	< 20 mg/Nm ³ < 50 mg/Nm ³ < 50 mg/Nm ³	< 20 mg/Nm ³ < 50 mg/Nm ³ < 50 mg/Nm ³	< 20 mg/Nm ³ < 50 mg/Nm ³ < 50 mg/Nm ³
Limits of uses	Low concentrations Presence of halogenated organic compounds ; Energy consumption outside autothermal conditions.	Presence of halogenated organic compounds ; Presence of particulate matter ; .	Presence of halogenated organic compounds ; Presence of catalyst poisons ; Presence of Particulate matter ; Risks of high concentrations	Presence of halogenated organic compounds ; Presence of catalyst poisons ; Presence of Particulate matter ; Risks of high concentrations

	Biological destruction	Adsorption on activated carbon	Absorption in heavy oil	Cryogenic condensation
Ranges of concentrations	Adapted to very low concentrations C < 1 à 2 g/Nm ³	C < 15 g/Nm ³	C < 10-15 g/Nm ³	C > 10 g/Nm ³
Waste gas flow rates	1 000 à 100 000 Nm ³ /h	1 000 to 100 000 Nm ³ /h	1 000 to 100 000 Nm ³ /h	1 000 to 5 000 Nm ³ /h
Performances (C eq)	100-150 mg/Nm ³	50 to 100 mg/Nm ³	50 to 100 mg/Nm ³	50 to 100 mg/Nm ³
Limits of uses	non biodegradable VOCs, Temperature of waste gases to be treated Non permanent release of NMVOC.	Number of VOCs Presence of particulate matter ; Presence of polymerisable compounds ; Treatment of recovered products.	Number of VOCs Capacity of absorption of VOCs; Treatment of recovered products.	Number of VOCs High volatile compounds Humidity ; Treatment of recovered products.

5.4 Costs

The estimation of investments and operating costs for VOC emission reduction options/techniques is important when choosing from the wide range of measures and, on a macroeconomic level, when developing a national or regional emission control strategy. It must be borne in mind that specific figures are highly dependent on factors such as plant capacity, removal efficiency, VOC concentration in the raw gas, type of technology, and the choice of new installations as opposed to retrofitting. These parameters, and thus the costs incurred as well as the resulting ranking of measures in terms of costs, may be highly case-specific, for instance for retrofit cases, and examples should not be generalised.

EGTEI documents defining the methodologies used to estimate costs for waste gas treatment techniques are available. Documents on oxidation, carbon adsorption and biofiltration are available at: http://citepa.org/forums/egtei/egtei_doc-VOC_abatement_tech.htm.

Investments and operating costs depend particularly on flow rates and VOC concentrations to be treated. Costs are provided in chapter 7.

5.5 Side effects

Side effects of emission abatement options/techniques can be positive or negative and should be accounted for. Side effects can generally be limited by properly designing and operating the facilities. Side effects include:

- Impacts on energy consumption and hence greenhouse gas emissions,
- Impacts on other air pollutants,
- Impacts on the use of natural resources,
- Cross-media effects, e.g. on waste or water.

Reduction technique	Positive side effects	Negative side effect
Oxidation	Possible co-treatment of odours	Energy consumption and GHG emissions in case of non autothermal conditions
Adsorption	Possible co-treatment of odours	Possible increase of energy consumption for steam generation
Cryogenic condensation	Possible co-treatment of odours	Energy consumption to produce liquid nitrogen

5.6 References used in chapter 5

[1] Council Directive 1999/13/EC of 11 March 1999 on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain activities and installations Official Journal L 085, 29/03/1999 P. 0001 - 0022

[2] Directive 2004/42/CE on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain paints and varnishes and vehicle refinishing products and amending Directive 1999/13/EC

[3] US EPA - Protocol for equipment leak - Emission estimates
EPA 453-95-017 – 1995

[4] CEN 2005. Fugitive and diffuse emissions of common concern to industry sectors. Measurement of fugitive emission of vapours generating from equipment and piping leaks – Draft standard N° pr EN 15446 – Brussels – European comity of normalisation

[5] European Commission - reference document on BAT in surface treatment with solvent 2007

[6] European Commission - reference document on BAT in common waste water and waste gas treatment / management systems in the chemical sector – february 2003.

[7] REGULATION (EC) No 1272/2008 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006

[8] Joint Service Pollution Prevention and Sustainability Technical Library
<http://205.153.241.230/topics/airpollution.html>

6 General issues for dust

6.1 General issues on dust

Dust or particulate matter (PM) refers to a complex mixture of small to tiny particles and liquid droplets suspended in air. Sizes of dust range from several nanometers up to 100 micrometers (µm). dust may be differentiated according to the aerodynamic diameter into:

- large particles with an aerodynamic diameter of more than 10 µm,
- coarse particles with an aerodynamic diameter of 2.5 to 10 µm,
- fine particles with an aerodynamic diameter of less than 2.5 µm,
- ultrafine particles with an aerodynamic diameter of less than 0.1 µm,

and more particular into:

- Total Suspended Particles (TSP) as the sum of fine, coarse and large particles,
- PM₁₀: The mass of particulate matter that is measured after passing through a size-selective inlet with a 50 % efficiency cut-off at 10 µm aerodynamic diameter,
- PM_{2.5} : the mass of particulate matter that is measured after passing through a size-selective inlet with a 50 % efficiency cut-off at 2.5 µm aerodynamic diameter;
- PM₁: the mass of particulate matter that is measured after passing through a size-selective inlet with a 50 % efficiency cut-off at 1 µm aerodynamic diameter;.

Besides this size dependent classification, dust is also differentiated according to its origin into primary and secondary dust. Primary dust comprises mainly unburned fuel (hydrocarbons), elemental carbon (soot), sulphates, and mineral salts as well as alkali and heavy metals [1]. Secondary PM is formed in the atmosphere of the precursors ammonia, sulphuric acid, nitric acid and NMVOC-related organic oxidation products [1].

Inhaling dust may cause negative health effects [2] like asthma, lung cancer, cardiovascular issues, and premature death. Health effects are related to particle size as large particles can be filtered out in the nose and throat. Particles with a size less than about 10 µm can enter the bronchi and the lungs, particles less than 2.5 µm in diameter the gas-exchange regions of the lung, and particles less than 0.1 µm can enter via the lungs into other organs. Therefore, the potential for negative health effects increases with decreasing particle diameter. Besides particle size also the chemical composition, e.g. carcinogenic components, and solubility of the particle in the lung has an impact on the potential health effects. Health effects are expected to be related to the number of smaller particles whereas most measurements refer to the particle mass which is in general dominated by the larger particles within the size fraction.

Furthermore, dust generates haze with effects on visibility and radiation balance. Soot and sulphate aerosols have a cooling effect on climate.

For PM, there are several natural and anthropogenic sources with differences in the size and the chemical composition of the generated dust. Dust formation may result from:

- mechanical processing of solid matter (crushing, grinding, surface processing, abrasion etc.),
- chemical and physical reactions (incomplete combustion, gas-to-particle conversion, condensation, deposition etc.),
- exposure of solid matter (wind erosion etc.)
- re-suspension of dust (from roads, stockpiles etc.).

Published measurement data on the share of PM_{2.5} and PM₁₀ in waste gas is scarce and/or of limited quality. Therefore the following tables citing calculated shares as used in the RAINS/GAINS model are presented.

Table 7: shares of PM_{2.5} and PM₁₀ in TSP as used in RAINS (2002) [15]

Sector Name	RAINS-Code(s)	Unit	PM _{2.5}	% PM _{2.5}	PM ₁₀	%PM ₁₀	TSP
Coal, grate (in industry, raw gas)				7%		20%	
Coal, fluidized (in industry, raw gas)				5%		26%	
Brown coal, pulverized (in industry, raw gas)				10%		35%	
Hard coal, pulverized (in industry, raw gas)				6%		23%	
Derived coal (in industry, raw gas)				45%		79%	
Biomass (in industry, raw gas)				77%		89%	
Waste (in industry, raw gas)				23%		38%	
Coal, grate (in power plants, raw gas)				14%		37%	
Coal, fluidized (in power plants, raw gas)				5%		26%	
Brown coal, pulverized (in power plants, raw gas)				10%		35%	
Hard coal, pulverized (in power plants, raw gas)				6%		23%	
Hard coal, wet bottom (in power plants, raw gas)				21%		23%	
Derived coal (in power plants, raw gas)				45%		79%	
Biomass (in power plants, raw gas)				77%		89%	
Waste (in power plants, raw gas)				23%		38%	
Coal, stoves and boilers (domestic)				13%		90%	
Coal, large boilers (residential)				7%		20%	
Derived coal (residential)				45%		79%	
Biomass, stoves and boilers (domestic)				93%		96%	
Biomass, large boilers (residential)				77%		89%	
Waste (residential)				60%		90%	
Fireplaces, stoves (wood burning in Eastern Europe)	DOM_FPLACE, DOM_STOVE	kt/PJ	0,279	93%	0,288	96%	0,3
Small domestic boilers (wood burning in Eastern Europe)	DOM_SHB_M, DOM_SHB_A	kt/PJ	0,093 - 0,23	37% - 92%	0,096 - 0,24	37% - 96%	0,1 - 0,25
Large residential boilers (wood burning in Eastern Europe)	DOM_MB_M, DOM_MB_A	kt/PJ	0,077 - 0,15	39% - 75%	0,089 - 0,18	45% - 90%	0,1 - 0,2
Industry (wood burning in Eastern Europe)	PP_, IN_, CONV_COMB	kt/PJ	0,185	77%	0,214	89%	0,24
Fireplaces, stoves (wood burning in Western Europe)	DOM_FPLACE, DOM_STOVE	kt/PJ	0,067 - 0,186	34% - 93%	0,07 - 0,192	35% - 96%	0,072 - 0,2
Small domestic boilers (wood burning in Western Europe)	DOM_SHB_M, DOM_SHB_A	kt/PJ	0,06 - 0,167	33% - 93%	0,062 - 0,17	34% - 94%	0,065 - 0,18
Large residential boilers (wood burning in Western Europe)	DOM_MB_M, DOM_MB_A	kt/PJ	0,05 - 0,12	33% - 80%	0,06 - 0,134	40% - 89%	0,065 - 0,15
Industry (wood burning in Western Europe)	PP_, IN_, CONV_COMB	kt/PJ	0,185	77%	0,214	89%	0,24

Table 7: shares of PM_{2.5} and PM₁₀ in TSP as used in RAINS (2002) [15]

Sector Name	RAINS-Code(s)	Unit	PM _{2.5}	% PM _{2.5}	PM ₁₀	%PM ₁₀	TSP
Power plants (stationary combustion of heavy fuel oil)	PP_NEW, PP_EX	kt/PJ	0,0093	60%	0,0132	85%	0,0155
Conversion (stationary combustion of heavy fuel oil)	CON_COMB	kt/PJ	0,0117	60%	0,0166	85%	0,0195
Industry (stationary combustion of heavy fuel oil)	IN_BO, IN_OC	kt/PJ	0,0104	60%	0,0147	85%	0,0173
Residential (stationary combustion of heavy fuel oil)	DOM	kt/PJ	0,0095	25%	0,0247	65%	0,038
Power plants (stationary combustion of light fuel oil), new	PP_NEW	kt/PJ	0,0004	18%	0,0011	50%	0,0022
Power plants (stationary combustion of light fuel oil), existing	PP_EX	kt/PJ	0,0007	19%	0,0018	50%	0,0036
Conversion (stationary combustion of light fuel oil)	CON_COMB	kt/PJ	0,0004	11%	0,0018	50%	0,0036
Industry (stationary combustion of light fuel oil)	IN_BO, IN_OC	kt/PJ	0,0003	14%	0,0011	50%	0,0022
Residential (stationary combustion of light fuel oil)	DOM	kt/PJ	0,0007	41%	0,0009	53%	0,0017
Power plants (stationary combustion of natural gas)	PP_NEW, PP_EX	kt/PJ	0,0001	100%	0,0001	100%	0,0001
Conversion (stationary combustion of natural gas)	CON_COMB	kt/PJ	0,0001	100%	0,0001	100%	0,0001
Industry (stationary combustion of natural gas)	IN_BO, IN_OC	kt/PJ	0,0001	100%	0,0001	100%	0,0001
Residential (stationary combustion of natural gas)	DOM	kt/PJ	0,00003 - 0,0002	100%	0,00003 - 0,0002	100%	0,00003 - 0,0002
Coke Production	PR_COKE	kt/ton	1,9971	40%	3,3618	68%	4,976
Sinter processes	PR_SINT	kg/ton sinter	0,557	7%	1,285	15%	8,563
Sinter fugitive	PR_SINT_F	kg/ton sinter	0,104	7%	0,24	15%	1,6
Pellet plant	PR_PELL	kg/ton pellet	0,03	100%	0,03	100%	0,03
Pig iron production	PR_PIGI	kg/ton pig iron	0,15	10%	0,24	16%	1,48
Pig iron production (fugitive)	PR_PIGI_F	kg/ton pig iron	0,15	6%	0,25	10%	2,5
Open-hearth furnace	PR_HEARTH	kg/ton steel	6,33	60%	8,76	83%	10,55
Basic oxygen furnace	PR_BAOX	kg/ton steel	10,45	50%	14,63	70%	20,9
Electric arc furnace	PR_EARC	kg/ton steel	7,55	43%	10,18	58%	17,55
Iron foundries	PR_CAST	kg/ton iron	10,68	71%	13,55	90%	15,05
Iron foundries (fugitive)	PR_CAST_F	kg/ton iron	1,38	24%	2,82	49%	5,75
Aluminum production (primary)	PR_ALPRIM	kg/ton aluminum	18,5	39%	27,26	58%	47
Aluminum production (secondary)	PR_ALSEC	kg/ton aluminum	5,195	44%	6,93	58%	11,9
Other Non-ferrous metals	PR_OT_NFME	kg/ton metal	12,3	82%	13,8	92%	15
Cement production	PR_CEM	kg/t cement	23,4	18%	54,6	42%	130
Lime production	PR_LIME	kg/t lime	1,4	1%	12	12%	100
Petroleum refining (refineries)	PR_REF	kg/t crude oil	0,096	79%	0,12	98%	0,122
Fertilizer production	PR_FERT	kg/t	18	36%	30	60%	50
Carbon Black production	PR_CBLACK	kg/t	1,44	81%	1,6	90%	1,78
Glass production	PR_GLASS	kg/t glass	2,96	91%	3,09	95%	3,25
Other production (PVC, gypsum, glass fibre)	PR_OTHER	kg/ton product	0,5 - 8	3% - 46%	2 - 15	11% - 86%	5 - 17,5

Major stationary sources of dust emissions are therefore combustion processes, in particular of coal, fuel oil and biomass but also of black liquor in paper industry, industrial processes like sintering, cement production etc. as well as storage, handling and mechanical processing of materials.

In order to reduce dust formation and dust emissions different types of measures like energy efficiency improvements (cf. Chapter 2.2), fuel switch, fuel cleaning, better handling of materials as well as abatement measures are applied. To achieve the most efficient dust reduction, beyond energy management measures, a combination of measures should be considered. To identify the best combination of measures a site-specific evaluation is needed.

6.2 Fuel switching

Fuel switching is an important option to reduce dust emissions from combustion but is governed by country specific conditions such as infrastructure and energy policy. Dust emissions are in general lower if the fuel allows a more homogenous combustion, contains less sulphur and less ash but more hydrogen. Therefore, combustion of natural gas is in general associated with low emissions¹ whereas high dust emissions result from combustion of fuel oil, biomass and coal if no abatement measures are applied. The choice of the fuel may also have effects on other emissions like sulphur, NO_x and greenhouse gas emissions as well as on applicability and need of abatement measures.

6.3 Fuel cleaning

Fuel cleaning is important for coal and fuel oil.

Conventional coal cleaning techniques rely on gravity-based separation of ash and sulphur compounds using jigs, dense-medium baths, cyclones or flotation of grinded coal. While 60 to 90% and 85 to 98% of the heating value of the coal is retained, ash removal can reach 60% and total sulphur removal 10 to 40%. Both sulphur and ash removal contributes to a reduction of dust emissions. Sulphur removal increases with the content of pyritic sulphur in the coal [4]. Advanced techniques are mostly based on:

- advanced physical cleaning (advanced froth floatation, electrostatic, heavy liquid cycloning),
- aqueous phase pre-treatment (bioprocessing, hydrothermal, ion exchange),
- selective agglomeration (Otisca, LICADO, spherical agglomeration Aglofloat),
- organic phase pre-treatment (depolymerisation, alkylation, solvent swelling, catalyst addition (e.g., carbonyl), organic sulphur removal).

These advanced coal cleaning techniques are still in development or demonstration phase [4]. Besides a reduction of sulphur and dust emissions, reported advantages are lower transportation costs if coal is cleaned already at the mine, higher boiler availability, less boiler slagging and fouling, less wear on equipment, lower dust load. Disadvantages are energy loss from cleaning (2-15%), energy costs for the processes and an increased moisture content of the coal if water-based processes are used [4].

Fuel cleaning for fuel oil is common practice in order to achieve low sulphur fuels which are e.g. required in the EU by Directive 1999/32/EC (heavy and light fuel oil less than 1% resp. 0.1% wt). Removing of sulphur reduces sulphur based dust emissions.

6.4 Primary measures

Unloading, handling and storage of solids

During unloading, storage and handling, e.g. loading, of solids dust emissions might occur. In general particle size of dust from unloading, storage and handling of solid is larger than dust from e.g. combustion. The use of enclosed or housed systems, e.g. covered continuous conveying systems, and reducing of drop heights may reduce dust emissions from unloading and handling [3]. Approaches to minimise dust from storage can be differentiated into primary measures which reduce emissions and secondary measures which aim at limiting the distribution of the dust [2]. Primary measures can be further differentiated into organisational, constructional, and technical measures. Technical primary measures are wind protection, covering or avoidance of open storage, and moistening of the open

storage, e.g. by a sprinkler systems. Secondary measures are spraying, water curtains and jet spraying as well as installation of filters in e.g. silos [2]. Spraying water is also a measure to reduce dust emissions from construction sites.

Capture of emissions

A prerequisite for later dust abatement is the capture of fugitive dust emissions, e.g. in the iron and steel industry, and venting to dust control systems.

Combustion technique and optimization

A smooth, continuous and complete combustion generates less dust emissions. An optimised air supply, mixing of fuel and air as well as burner/boiler design reduce the formation of soot and other substances resulting from incomplete combustion. Therefore good housekeeping of boilers as well as the use of new, more efficient boilers and stoves, especially in the residential and commercial sector, may reduce dust emissions. In this way dust emissions from wood stoves can be considerably reduced. Changing from batch to continuous operation of boilers allows for a better combustion control and reduces dust emissions. Primary measures for NO_x reduction may, however, increase soot formation (cf. Chapter 4) A lowering of the combustion temperature reduces ash volatilization. Fuel additives and sorbents are proposed to reduce the formation of fine particles and metals in the fine particles. In Integrated gasification combined cycle (IGCC) the fuel is gasified under reducing conditions to syngas. The syngas is then cleaned and burnt in either air or oxygen. This allows the achievement of very low dust emission levels. IGCC is seen as one of several key technologies in the framework of carbon capture and storage (CCS). So far its application is restricted to few, mostly demonstration plants. With CCS-IGCC could become commercially available around 2020 [5].

6.5 Secondary measures

Secondary measures (add-on or end of pipe technologies) reduce the emissions of PM which is already in the flue gas. Several main principles are used for secondary measures:

- inertia of particles,
- sieving and adsorption,
- electrostatic charging of particles and subsequent precipitation making use of an electric field,
- scrubbing.

The following secondary measures¹ are mainly in use, each with its specific advantages and disadvantages:

- **Gravity settling chamber:** In gravity settling chambers the flow rate of the air is reduced so that larger particles sink and settle. Gravity settling chambers are only useful for removing the largest particles in terms of "pre-cleaning". The minimum particle size removed by gravity settling chambers is >20 µm [1].
- **Cyclone:** In cyclones inertia of particles are used for dust removal. In a cyclone the flue gas is forced (usually via a conical shaped chamber) into a circular motion where particles are forced by inertia to the cyclone walls where they are collected. Collection efficiency depends strongly on particle size and increases with the pollutant loading. For conventional single cyclones it is estimated to be 70-90% for TSP, 30-90% for PM₁₀ and 0-40% for PM_{2.5} [6]. The minimum particle size removed by cyclones is 5-25 µm and 5 µm in multicyclones [1]. Conventional cyclones are therefore referred to as "pre-cleaners". Conventional cyclones alone are not BAT for industrial installations but could be an option to reduce dust emissions from small combustion installations, e.g. in households or in the commercial sector. High efficiency cyclones removing 60-95% of PM₁₀ and 20-70% of PM_{2.5} have been developed but at the expense of a high pressure drop leading to high energy and hence operation costs [6]. Achieving higher removal efficiencies in cyclones is mainly a problem of the resulting pressure drop. High throughput cyclones have been designed on purpose for removing just the larger dust fraction at the expense of only low pressure drop. In multicyclones many small cyclones

¹ The performance data in the following mainly refers to boiler installations

operate in parallel achieving removal efficiencies similar or superior to high efficiency cyclones (cf. [6]). Application of cyclones as a pre-cleaner to remove abrasive particles may increase the lifetime of other abatement equipment. Cyclones are also used to recover recycling products, process materials etc. from the flue gas, e.g. in the ferrous and non-ferrous metals industry. Advantages of cyclones are: low investments, low operating and maintenance costs relative to the amount of PM removed, temperature and pressure range only limited by material, collection of dry material, relatively small in size. Disadvantages include low removal efficiencies for fine PM (or alternatively high pressure drops) and non-applicability for sticky materials.

- **Electrostatic precipitator (ESP):** The principle behind ESP is that particles of the flue gas stream are electrostatically charged when passing through a region with gaseous ions (corona) generated by electrodes at high voltage (around 20 to 100 kV). The charged particles are then redirected in an electric field and settle at the collector walls. As large particles absorb more ions than smaller ones, ESP removal efficiency is higher for larger particles. New ESP typically achieve PM removal efficiencies of 99 to more than 99.99% in the range 0.01 to >100 µm, older ones 90 to 99.9% [1], [7], [8]. The minimum particle size removed by ESP is <1 µm [1]. Removal efficiencies are lowest for particles with a diameter of 0.1 to 1 µm. Efficiency depends on the ESP size (collection area) but also on dust resistivity, temperature, chemical composition of the dust and gas and particle size distribution. Dust at the collectors can be removed either dry or wet by a spray of usually water (dry or wet ESP). Dry ESPs are more common as dry collected dust is easier to handle than a slurry which requires after treatment. Wet ESPs need noncorrosive materials. However, removal of particles with extremely low or high resistivity is difficult in dry ESPs whereas wet ESPs can also collect particles with high resistivity as well as sticky particles, mists or explosive dusts. Wet ESPs show also higher efficiencies for smaller particles. Injection of conditioning gases, liquids or solids, in particular water and SO₃, may improve removal efficiencies [1]. Advantages of ESPs are in general very low pressure drops, very good removal efficiencies (but less pronounced for fine particles), low operating costs as well as wide applicability (sticky, glowing, high resistivity (wet ESP) particles, mists, acids, ammonia, exploding gases (wet ESP)) [1], [7], [8]. Disadvantages are high investments, high space demand, ozone formation due to high voltage, need for specialised personnel for high voltage, and limited applicability in case of varying flue gas conditions (flow rate, temperature, dust load, composition of dust) as well as necessary after treatment of slurry (wet ESPs), but almost closed water loops are achievable [1], [7], [8].
- **Fabric filter (FF):** In a FF the flue gasses pass through a permeable fabric where larger particles are sieved or adsorbed. The filter cake made up of collected particles supports the collection of further particles. As pressure drop increases with filter cake thickness the fabric filter needs to be cleaned from time to time. Three main cleaning mechanisms are applied: pulse jet filters where filters are cleaned by a pulse of pressurized air from the other side, shaker mechanisms and reverse gas flow. Pulse jet filters are today the most common type as they demand less space, are less expensive and applicable for high dust loadings and cause constant pressure drop [1], [9], [10]. Removal efficiencies are 99 to 99.99% for new and 95 to 99.9% for older installations [1], [9], [10] and depend on filtration velocity, particle and fabrics characteristics and applied cleaning mechanism. FF is in particular able to remove fine and ultrafine dust. Flue gas conditioning using mainly elemental sulphur, ammonia and SO₃ is applied to achieve higher removal rates, reduce pressure drop, and reduce re-entrainment of particles [1]. New developments are the addition of activated carbon or lime to achieve reactions in the filter cake as well as a catalytic filter material [1]. Flue gas temperature depends on the filter material used and the dew point of the flue gas and is in general between 120-180°C [1]. Advantages of FF are very low emission levels even down to ultrafine particles (depending on fabric) and achieved independent from dust loading, flow rate (e.g. start-ups) and dust type (e.g. resistivity), relatively low investments, simple operation and in general no corrosion problems. Disadvantages are relatively high maintenance and operating costs due to replacement of filter bags (lifetime depends on temperature and dust) and pressure drop and in particular limitations in applicability in moist environments and for hygroscopic, glowing and sticky particles as well as for acids and ammonia and exploding gases [1], [9], [10]. Large particles need to be removed in advance [1]. Bypassing is necessary during failure.
- **Wet scrubber:** Injecting water into the flue gas stream leads to formation of water droplets which with dust, forms a slurry. Scrubbers are mainly used for SO_x removal but reduce also dust. Removal efficiencies are up to 80% for spray towers as well as dynamic and collision scrubbers and up to 99 % for venturi scrubbers [1]. The minimum particle size removed by

spray towers is >10 µm, by dynamic and collision scrubbers > 2.5 µm and by venturi scrubbers >0.5 µm. Advantages of wet scrubbers are simultaneous removal of SO_x and dust (and even other pollutants like HCl and HF), low maintenance, rather high removal efficiencies (in particular venturi scrubbers), few application limits (flow rate fluctuations, hot or cold, wet and corrosive gases, mists are uncritical) and reduced explosion risks from dust. Disadvantages are waste generation (slurry), high maintenance costs due to potentially high pressure drop, corrosion problems and rather low removal efficiency for very fine particles [1].

- Other dust control techniques include:
 - **COHPAC™ and TOXECON™ technologies:** COHPAC™ (Compact Hybrid Particulate Collector) and TOXECON™ are multi multi-pollutant control technologies for mercury, dioxins but also other pollutants including fine particles developed and applied in the U.S.A. In COHPAC™ a FF is installed downstream of an existing ESP. As the ESP removes most of the dust, the filtration rate of the FF can be increased substantially while keeping a modest pressure drop [11]. ESP might also lead to agglomeration of very fine particles which can be then removed in the FF. TOXECON™ refers to the injection of a dry sorbent like activated carbon between the ESP and FF.
 - **Indigo Agglomerator:** The Indigo Agglomerator forms large agglomerated particles by attaching fine particles to larger particles. The agglomerated particles can be easily removed using standard techniques like ESP. This technique allows also the reduction of mercury emissions [12].

To sum up, a variety of measures to reduce dust emissions exist. Some like cyclones are able to reduce the large and to some extent also the coarse fraction but are considerably less efficient for the fine fraction of dust. For fine and submicron dust fabric filters achieve very high removal efficiencies (up to 99.99% and above). Highly efficient ESPs, in particular Wet ESPs, as well as Venturi scrubbers may also achieve relatively high removal efficiencies for this size class up to 95% to 99%. Emerging techniques like the Indigo Agglomerator might contribute to increase ESP efficiency for fine particles by increasing the particle size.

However, when comparing removal efficiencies it need to be taken into account the characteristics of the dust and the flue gas as well as other parameters like dust load, flow rate, fluctuations as these factors may have a large impact on overall and size-specific removal performance. Furthermore removal rates largely depend on the specific design of the dust collector, e.g. on chosen filter material and ESP dimensioning, and in the end investment and operating costs.

Table 8: Removal efficiencies of dust abatement measures for different particles size for boiler plants

Category	Type	Subtype	Removal efficiencies [%]					
			submicron	fine		coarse		large
			<1 µm	0-2.5 µm		2.5-6 µm	6-10 µm	>10 µm
			RAINS*	US EPA**	RAINS**	US EPA**		RAINS**
Gravity and centrifugal collector	Gravity collector	high efficiency		3.6		5	6	
		medium efficiency		2.9		4	4.8	
		low efficiency		1.5		3.2	3.7	
	Centrifugal collector	high efficiency		80		95	95	
		medium efficiency		50		75	85	
		low efficiency		10		35	50	
Cyclone	Single cyclone			10		35	50	
	Multiple cyclone without fly ash reinjection			80		95	95	
	Multiple cyclone with fly ash reinjection			50		75	85	
	Cyclone/Multicyclone unspecified		11		30			70
ESP	Wet cyclonic separator			50		75	85	
	ESP	high efficiency	98.6	95	99	99	99.5	99.9
	ESP	medium efficiency (unspecified)	95.4		96			99
	ESP	low efficiency (unspecified)	91.96		93			95
	wet ESP		98.86		99			99.9
	ESP: boilers	medium efficiency		50		80	94	
		low efficiency		40		70	90	
	ESP: other than boilers	medium efficiency		80		90	97	
		low efficiency		70		80	90	
	Fabric filter	high temperature		99		99.5	99.5	
Fabric Filter	Fabric filter	medium temperature		99		99.5	99.5	
		low temperature	99.99	99	99	99.5	99.5	99.9
								99.98
	Spray tower			20		80	90	
Scrubber	Wet scrubber	high efficiency	95	90	96	95	99	99.5
		medium efficiency		25		85	95	
		low efficiency		20		80	90	
	Venturi scrubber			90		95	99	
Other	Process enclosed			1.5		3.2	3.7	
	Dust suppression by water sprays			40		65	90	
	Dust suppression by chemical stabilizer or wetting agents			40		65	90	
	Water curtain			10		45	90	
	Good practice: industrial processes (fugitive)	stage 1	20		10			15
	Good practice: industrial processes (fugitive)	stage 2	65.33		30			50
								75

* Kupiainen, K. & Z. Klimont (2004) Primary emissions of submicron and carbonaceous particles in Europe and the potential for their control. - IIASA Interim Report IR-04-079, 122 pp.
 ** Klimont, Z., J. Cofala, I. Bertok, M. Amann, C. Heyes & F. Gyarfas (2002): Modelling Particulate Emissions in Europe. - IIASA Interim Report IR-02-076, 179 pp.
 *** US EPA (1996): AP 42, Volume I, Fifth Edition, Appendix B.2 Generalized Particle Size Distributions

The selection of the most suitable measure depends on many factors related to e.g.:

- flue gas characteristics (dust concentration and characteristics like particle size distribution, resistivity, temperature, humidity, other pollutants present like acids, SO_x, etc.),
- flow rate and fluctuations of flue gas,
- operation mode of installation,
- process specifics in industrial processes,
- new installation or retrofitting, e.g. available space,
- emission levels to be achieved,
- side and cross media effects,
- operational safety and reliability,
- site specifics,
- costs.

6.6 *Costs of dust emission reduction techniques*

Costs are an important issue when selecting PM emission reduction techniques. The following expenses may be relevant [13]:

- imputed depreciation allowance and imputed interest,
- labour costs,
- expenses for auxiliary and operating materials,
- energy costs,
- maintenance and repair costs, expenditure on monitoring, expenses for external services,
- taxes, environmental levies (e.g. charges for waste water), fees, public charges.

Costs increase in general less than the capacity of the reduction technique so that larger units are often more cost-effective. Retrofitting of existing installations is often possible but in general at higher costs.

For ESP investments are relatively high whereas maintenance and operating costs are relatively low, in particular as a result of the low pressure drop. Other costs are related to personnel specialised for high voltage and in case of wet ESP costs for slurry treatment.

For fabric filters, investments are lower but maintenance and operating costs are higher as fabrics have to be changed regularly (depending on flue gas and dust characteristics) and as the pressure drop is modest to high.

6.7 *Side effects*

Side effects of emission abatement options/techniques can be positive or negative and should be accounted for. Side effects can generally be limited by properly designing and operating the facilities. Side effects include:

- Impacts on energy consumption and hence greenhouse gas emissions,
- Impacts on other air pollutants,
- Impacts on the use of natural resources,
- Cross-media effects, e.g. on waste or water.

A core side effect of dust emission reduction is the simultaneous reduction of heavy metals (except for mercury) [14]. Depending on its characteristics and chemical composition collected dust can be recycled, e.g. in iron and steel industry, or has to be disposed.

More specifically, the side effects to be considered with different PM emission reduction techniques are:

Electrostatic precipitator (ESP): For ESPs a main side effect is electricity consumption for producing the corona and the electric field. However, as pressure drop is low in ESPs, overall electricity consumption is considerably lower than in FF where high pressure drops have to be compensated for. In wet ESPs treatment of the slurry is necessary but water recirculation reaches almost 100% so that waste consumption is low. As ESPs have considerably lower removal efficiencies in the size range 0.1 to 1 µm removal of heavy metals in ESPs is far lower than in FF.

Fabric filters (FF): Fabrics have to be changed around every 2 to 4 years (lifetime depends on various factors) so that waste is generated if reprocessing of the fabrics is not possible. The pressure drop in FFs has to be compensated for by pumping leading to additional electricity consumption. As FFs are also very effective in removal of fine particles, they also effectively reduce emissions of heavy metals which are enriched in the sub-micrometer size range of dust in flue gases.

6.8 References used in chapter 6

- [1] Ohlström, M., J. Jokiniemi, J. Hokkinen, P. Makkonen, and J. Tissari (2006): Combating particulate emissions in energy generation and industry. Views and conclusions of the FINE Particles - Technology, Environment and Health Technology Programme, VTT Technical Research Centre of Finland.
- [2] Storage BREF (2006): Reference Document on Best Available Techniques for Emissions from Storage. – European Commission, 460 pp.
- [3] LCP BREF (2006): Reference Document on Best Available Techniques for Large Combustion Plants. – European Commission, 618 pp.
- [4] Worldbank: Coal Cleaning, <http://www.worldbank.org/html/fpd/em/power/EA/mitigatn/aqsocc.stm>, accessed 27.09.2008.
- [5] Results of work of the EGTEI expert sub-group on Emerging Technologies/Techniques. Report by the Chair of the Expert sub-group on Emerging Technologies/Techniques to the Working Group on Strategies and Review – 1 – 5 September 2008.
- [6] US EPA: EPA-CICA Air Pollution Technology Fact Sheet "Cyclones".
- [7] US EPA: EPA-CICA Air Pollution Technology Fact Sheet "Wet Electrostatic Precipitator (ESP) - Wire-Pipe Type".
- [8] US EPA: EPA-CICA Air Pollution Technology Fact Sheet "Dry Electrostatic Precipitator (ESP) - Wire-Plate Type".
- [9] US EPA: EPA-CICA Air Pollution Technology Fact Sheet "Fabric Filter, Pulse-Jet Cleaned Type".
- [10] US EPA: EPA-CICA Air Pollution Technology Fact Sheet "Fabric Filter, Mechanical Shaker Cleaned Type".
- [11] Miller, R., R. Chang & C.J. Bustard (2003): Effective use of both COHPACT™ and TOXECON™ technologies as the "Technology of the future" for particulate and mercury control on coal-fired boilers. - Text prepared for 2003 International Power-Gen Conference, Las Vegas, U.S.A.
- [12] Truce, R. (2008): Enhanced fine particle and mercury emission control using the Indigo Agglomerator. - VGB powertech 88, 95-101.
- [13] VDI 3800, Determination of costs for industrial environmental protection measures. Verein Deutscher Ingenieure, 2001.
- [14] Kraus, K., S. Wenzel, G. Howland, U. Kutschera, S. Hlawiczka, A. P. Weem and C. French (2006): Assessment of technological developments: Best available techniques (BAT) and limit values. Submitted to the Task Force on Heavy Metals, UNECE Convention on Long-range Transboundary Air Pollution.

7 Available techniques for different activities
