Final Technology Report

MCP Information exchange

Report for DG Environment
ENV.C.4/FRA/2015/0042

ED 10671 | Final Report for WG | Date 26/09/2019

Customer:

DG Environment, European Commission

Customer reference:

ENV.C.4/FRA/2015/0042

Confidentiality, copyright & reproduction:

Contact:

Alfredo López Carretero
Ricardo Energy & Environment
Gemini Building, Harwell, Didcot, OX11
0QR, United Kingdom

t: +34 626 804 934
e: alfredo.lopez@ricardo.com

Ricardo is certificated to ISO9001, ISO14001 and OHSAS18001

Author:

Alfredo Lopez, Thomas Gallauner, John Hekman, Sam Stephenson

Approved By:

Ben Grebot

Date:

26 September 2019

Ricardo Energy & Environment reference:

Ref: ED10671- Final Report for WG

Table of contents

Appendices

Appendix 1	Complete emissions questionnaire data analysis (HTML)
Appendix 2	Complete energy efficiency questionnaire data analysis (HTML)
Appendix 3	Complete technology descriptions
Appendix 4	Technology costs
Appendix 5	Engine types
Appendix 6	References

Acronyms

Acronym	Definition
AS:	Air staging
BAT-AEL:	Emission Level associated with the Best Available Techniques
BF:	Bag filter
BFB:	Bubbling fluidised bed
BOOS:	Burner out of service
CC:	Combined cycle
CCGT:	Combined-cycle gas turbine
CFB:	Circulating fluidised bed
CFBC:	Circulating FBC
CHP:	Combined heat and power
CO:	Carbon monoxide
COD:	Chemical oxygen demand
COG:	Coke oven gas
DF:	Dual fuel (engine type)
DLN:	Dry low NOx burner
DSI:	Duct sorbent injection
EER:	Energy efficiency range
EGR:	Flue-gas or exhaust-gas recirculation
ESP:	Electrostatic precipitator
ETS:	(European) Emissions Trading System
FBC:	Fluidised bed combustion
FC:	Fuel choice
FGD:	Flue gas desulphurisation (wet scrubber)
FS:	Fuel staging
GC:	Flue gas condenser
GD:	Gas diesel (engine type)
GF:	Grate firing
GT:	Gas turbine
HFO:	Heavy fuel oil
I&S:	Iron and Steel
IED:	Industrial Emissions Directive (2010/75/EU)
IPPC:	Integrated Pollution Prevention and Control
ISO:	International Organisation for Standardisation
KoM:	Kick-off meeting
LCP:	Large combustion plant
LHV:	Lower heating value
LNB:	Low-NOx burner
LNG:	Liquefied natural gas
MCP:	Medium combustion plant
MCPD:	Medium combustion plant directive
MIS:	Medium isolated system
MS:	(European) Member State

Acronym	Definition
NG:	Natural gas
NOX:	Nitrogen oxides ($NO + NO_2$, normally expressed as NO_2)
OCGT:	Open-cycle gas turbine
OPER:	Optimal performance emission range
OTNOC:	Other than normal operating conditions
PAH:	Polycyclic aromatic hydrocarbon
PC:	Pulverised combustion
PFBC:	Pressurised FBC
PM:	Particulate matter
PM10:	Particulate matter of less than 10 µm
PM2.5:	Particulate matter of less than 2.5 µm
SC:	Supercritical (steam)
SCR:	Selective catalytic reduction
SDA:	Spray dry absorber
SG:	Spark-ignited (engine type)
SIS:	Small isolated system
SNCR:	Selective non-catalytic reduction
SO2:	Sulphur oxide
SOX:	Sulphur oxides (SO_2 and SO_3)
TOC	Total organic carbon
TRL	Technology readiness level
US DOE:	United States Department of Energy
US EPA:	United States Environmental Protection Agency
USC:	Ultra-supercritical (steam)
VOC:	Volatile organic compound
WFGD:	Wet FGD
WG:	Working group

1 Introduction

1.1 The MCP information exchange

The Medium Combustion Plant (MCP) Directive sets emission limits for NO_x, SO_2 and dust for new and existing MCPs broken down by technology type, capacity and fuel type. The Directive entered into force on 18 December 2015 and Member States should have transposed it into national legislation by 19 December 2017.

Article 6(10) of the MCP Directive states the following: "*The Commission shall organise an exchange of information with Member States, the industries concerned and non-governmental organisations on the emission levels achievable with best available and emerging technologies and the related costs. The Commission shall publish the results of the exchange of information*." Article 12 of the MCP Directive requires the Commission to review and assess the need for action in relation to energy efficiency, CO emissions, the provisions concerning plants which are part of SIS or MIS, and Part 2 of Annex II in line with state-of the art technologies.

Ricardo was contracted by the European Commission to provide support for meeting its obligations under Articles 6(10) and 12 of the MCP Directive by organising and managing an information exchange process **to gather information from Member States, MCP operators and suppliers, abatement equipment suppliers and other relevant stakeholders on the environmental performance and costs of best available and emerging technologies to reduce emissions from MCPs**. The terms of reference for this support can also be found in Circabc[1]. The MCP Working Group (WG) was established to provide inputs to, and review the outputs of, the information exchange.

1.2 Objectives of the MCP information exchange

The overall objective of this information exchange was to provide support to the Commission to enable it to meet its obligations related to Articles 6(10) and 12 of the MCPD. The core element of the initiative was to analyse updated information on the environmental performance and costs of technologies to reduce emissions from MCPs. These include best available and emerging technologies.

1.3 Objective and scope of this document

This document or any other deliverable from this project will **not become legally binding.**

The aim of the report is to provide technical information on the capabilities of MCPs and the environmental performance of primary and secondary technologies used in these units to reduce their environmental impact.

The scope of this information exchange is similar to the framework and provisions of the MCPD with some exceptions such as:

- Definition of new plant: in order to capture the capabilities of plants recently commissioned in Europe this information exchange has considered “new plants” to be those which came into operation in 2016 and onwards. This differs from the MCPD.
- Pollutants covered by the study: this information exchange has gathered data from a wider set of pollutants than those covered by the MCPD.
- MCP plants in the scope: This study contains (limited) information on capabilities of some MCPs that might be out of the scope of the MCPD such as offshore plants. Data from these plants

---

[1] https://circabc.europa.eu/w/browse/f4bbf066-1905-4290-8ec2-3ef6507e10db

help to demonstrate the performance of different types of MCPs or technologies including those operating under certain constraints.

1.4 Methodology

This information exchange has not followed the same process as the so called “Sevilla Process” and requirements established under Article 13 of the Industrial Emissions Directive (IED) to review and develop BAT reference documents (BREFs).

This initiative is more focused and streamlined than other similar information exchange exercises performed in the context of the IED as well as wider initiatives. The overall timeline for this information exchange is 18 months.

The Kick-off Meeting (KoM) of the MCP WG held in March 2018 focused on the scope/priorities of the exchange of information, timeline, the strategy for data collection, specific tasks to be carried out by the members of the group and the stakeholders to be contacted. The design of the questionnaire was done in spring 2018 incorporating comments from WG members and findings from an initial test with a small number of operators.

The final meeting held in May 2019 was used to discuss the draft findings and resolve any outstanding issues of the information exchange with a view to conclude the technical discussions within the MCP WG. In between these meetings there was a co-ordinated exchange of information and further consultation to ensure that sufficient evidence was available to determine best available and emerging technologies for MCPs. The timetable for the steps for the MCP information exchange and the main milestones are summarised in **Error! Reference source not found.**.

Table 1-1 Timeline for MCP information exchange

Step	MCP information exchange milestone	Actual / forecast dates
1	Activation of WG: expressions of interest from interested parties and decisions on WG composition	January 2018
2	Dissemination of background paper for KoM	February 2018
3	KoM of the WG	6 March 2018
4	Design of the questionnaires	March 2018
5	Collection of information and data	Deadline August 2018
6	First draft technology report	March 2019
7	WG consultation	April-May 2019
8	Final draft technology report	mid May 2019
9	Final meeting	23 May 2019
10	Final technology report taking into account feedback received on the first draft	15 July 2019

1.5 This document

This document analyses the information provided by WG members and related technical literature. The most relevant information sources are the completed questionnaires provided by MCP operators. The structure for this document is as follows:

- Section 2 describes the technologies that can reduce the environmental impact of MCPs, both emerging and mature.
- Section 3 summarises the data from questionnaires and from related literature on environmental performance and technology cost.

  - Section 3.1 summarises MCP environmental data analysis from questionnaires.
  - Section 3.2 compares the findings from the questionnaire analysis in relation to emissions performance with relevant literature sources and existing legislation in selected Member States.
- Section 4 is focused on the costs associated with selected technologies.
- Section 5 presents proposals for what may be considered best available technologies for each MCP technology-fuel-pollutant category.

The term “survey“ used throughout this document refers to data gathered via questionnaires in this information exchange.

2 Technologies to reduce the environmental impacts of MCPs

This section provides an introduction to the technologies used in MCPs to reduce their environmental impacts. This section includes short descriptions of technologies and the criteria to classify them. Appendix 3 includes a more detailed technology description including applicability restrictions.

2.1 Criteria to classify technologies

The technologies presented in this document are classified according to the following criteria: their maturity and their environmental performance.

The term ‘primary measure’ is used in this document to refer to preventive technologies or design options that lead to lower emissions from a combustion unit. The term ‘secondary measure’ is used to refer to abatement technologies that reduce the emissions that have been generated by the combustion unit. These are also called end of pipe technologies.

2.1.1 Maturity of technologies to reduce environmental impact

Technology readiness level (TRL) is a rating method for estimating technology maturity. TRL scores are based on a scale from 1 to 9 with 9 being the most mature technology. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology. TRL has been in widespread use at NASA since the 1980s where it was originally invented. The European Commission advised EU-funded research and innovation projects to adopt the scale in 2010 which they did from 2014 in its Horizon 2020 program.

From a technology development angle, this document uses the following criterion and terminology to distinguish mature (proven) technologies from developing (novel) ones:

(a) Candidate best available technologies: those technologies tested or used at commercial plants. These technologies will score 9 in the TRL scale. This group of technologies will undergo a deeper assessment step to select best performing ones. These are described in Section 2.2.

(b) Emerging technologies are those not yet tested at commercial plants which will score between 6 and 9 in the TRL scale. These will be ready for testing in large pilot plants, semi works (large pilot plants) or demo sets. These are described in Section 2.3.

(c) Other immature technologies with a TRL score below 6. These technologies have not been included in the report.

2.1.2 Performance of technologies to reduce environmental impacts

This document aims to select technologies that reduce the environmental impacts of MCPs. It assigns the term “best available technologies” to those technologies that, when implemented in MCPs, can deliver optimal performance ranges. Table 2-1 describes the numerical criteria used to select the best available technologies. Regarding emissions reduction technologies, best available technologies are those that deliver the Optimal Performance Emission Range (OPER) whereas for energy efficiencies technologies, best available technologies are those that deliver the Energy Efficiency Range (EER) delivered by best performers. Energy efficiency will depend on the plant arrangement: e.g. a mechanical drive plant will have different efficiency than a CHP plant.

These two terms (OPER and EER) are used to support the selection of the best performing plants from the MCP sample assessed during this study.

Table 2-1 Terms and concepts to support criteria

Acronym	Term	Description
OPER	Optimal Performance Emission Range	Emission value range delivered by best performers on a given MCP plant category (questionnaire data collection): from **minimum emission value to 25th percentile**
EER	Energy Efficiency Range	Energy efficiency value range delivered by best performers (questionnaire data collection): from **maximum efficiency value to 75th percentile**

The evidence to support this classification can be found in Section 3.1 (EU plant capabilities). The analysis to derive the best available technologies for each environmental issue is included in Section 5 (Best available technologies to reduce the environmental impact of MCPs).

2.2 Mature technologies used in MCPs

This section describes mature technologies that are commercially available and can reduce the environmental impact of MCPs. These can be considered **candidate** best available technologies. These technologies have been identified from relevant literature sources (mostly from BREFs). Some of these technologies reduce environmental impacts for more than one environmental issue.

The emissions performance of these technologies is described in Section 3.2 (based on questionnaires and literature). The costs of these technologies can be found in Section 4.2.

2.2.1 Generic technologies for MCPs

There are some candidate best available technologies that are generally applicable and generate impacts across a wider range of issues (e.g. emissions of multiple pollutants). These are described in Table 2-2 below, additional information on each technology can be found in Appendix 3.

Table 2-2 Generic candidate best available technology for MCPs

Candidate best available technology	Description	Most commonly used (1)
Advanced control system (ACS)	The use of a computer-based automatic system to control the combustion efficiency and support the prevention and/or reduction of emissions. This also includes the use of high-performance monitoring.	Gas turbines, engines and boilers
Combustion optimisation (CO) (Optimisation of burning)	Technologies taken to maximise the efficiency of energy conversion, e.g. in the furnace/boiler, while minimising emissions (in particular of CO). This is achieved by a combination of techniques including good design of the combustion equipment, optimisation of the temperature (e.g. efficient mixing of the fuel and combustion air) and residence time in the combustion zone and use of an advanced control system.	
Use of clean fuels (fuel choice-FC)	Choosing fuels with low Sulphur, Nitrogen and ash content.	
Treatment of fuels (TF)	Physical, chemical, or biologic treatment of fuels. (e.g. activated carbon for desulphurisation)	Liquid and gaseous fuels
Fuel blending and mixing (FB) (Use of fuels of homogeneous and constant quality)	High quality fuels allow a better tuning of the combustion process. Ensure stable combustion conditions and/or reduce the emission of pollutants by mixing different qualities of the same fuel type.	Gas turbines, engines and boilers
(Boiler) Combustion unit design and size (CDS)	Good design of furnace, combustion chambers, burners and associated devices.	Boilers

(1) See Appendix 3 and section 5 of this document for a more complete set of applicability restrictions.

2.2.2 Technologies to maximise energy efficiency

This section lists candidate best available technologies that can improve the energy efficiency of MCPs. These are described in Table 2-3 below, additional information on each technology can be found in Appendix 3. The technologies listed have varying applicability and impacts on efficiency for different kinds of MCPs. Their impact on efficiency may vary with various factors such as the kind of combustion system, the fuel used and/or plant load.

Generic technologies mentioned in section 2.2.1, such as combustion optimisation, also apply here.

Table 2-3 Candidate best available technologies to increase energy efficiency for MCPs

Candidate best available technology	Description	Most commonly used (1)
Combined heat and power (CHP)	Cogeneration is the recovery of heat (mainly from the steam system) for producing hot water / steam to be used in industrial processes/activities or in district heating. Additional heat recovery is possible from: the flue-gas; grate cooling; the circulating fluidised bed. The heat from the combustion plant (e.g. turbine, engine) flue-gases may be used for steam production in a heat recovery boiler (also called heat recovery steam generator) or be extracted partially (or sometimes fully) and used for steam supply to consumers, who can then use the steam in their own processes or for other purposes such as district heating or seawater desalination.	New plants
Combined cycle (CC)	Combination of two or more thermodynamic cycles, e.g. a Brayton cycle (gas turbine/combustion engine) with a Rankine cycle (steam turbine/boiler), to convert heat loss from the flue-gas of the first cycle to useful energy by subsequent cycle(s).	New plants
Flue-gas condenser (GC)	A heat exchanger where water is preheated by the flue-gas before it is heated in the steam condenser. The vapour content in the flue-gas thus condenses as it is cooled by the heating water. The flue-gas condenser is used both to increase the energy efficiency of the combustion unit and to remove pollutants such as dust, SO_X, HCl, and HF from the flue-gas.	CHP boilers
Dry bottom ash handling (DBA)	Dry hot bottom ash falls from the furnace onto a mechanical conveyor system and, after redirection to the furnace for reburning, is cooled down by ambient air. Useful energy is recovered from both the ash reburning and ash cooling	Solid fuel boilers
Supercritical steam conditions (SCS)	The use of a steam circuit, including steam reheating systems, in which steam can reach pressures above 220.6 bar and temperatures of > 540°C[2].	Boilers
Wet stack (WST)	The design of the stack in order to enable water vapour condensation from the saturated flue-gas and thus to avoid using a flue-gas reheater after the wet scrubber.	Units with wet scrubbers.

(1) See Appendix 3 and section 5 of this document for a more complete set of applicability restrictions.

---

[2] https://www.researchgate.net/publication/251667915_Analysis_of_small_size_combined_cycle_plants_based_on_the_use_of_supercritical_HRSG

2.2.3 Technologies to reduce NO_x and or CO emissions

This section lists candidate best available technologies that can reduce emissions of CO and/or NO_x from MCPs. These are described in Table 2-4 below, additional information on each technology can be found in Appendix 3. Generic technologies mentioned in section 2.2.1, such as combustion optimisation, also apply here.

Table 2-4 Candidate best available technologies to reduce emissions of CO and/or NOx from MCPs

Candidate bes available technology	Description	Most commonly used (1)
Air staging (AS)	The creation of several combustion zones in the combustion chamber with different oxygen contents for reducing NO_x emissions and ensuring optimised combustion. The technique involves a primary combustion zone with sub-stoichiometric firing (i.e. with deficiency of air) and a second reburn combustion zone (running with excess air) to improve combustion. Some old, small boilers may require a capacity reduction to allow the space for air staging.	Boilers
Dry low-NO_x burners (DLN)	Gas turbine burners that include the premixing of the air and fuel before entering the combustion zone. By mixing air and fuel before combustion, a homogeneous temperature distribution and a lower flame temperature are achieved, resulting in lower NO_x emissions.	Gas turbines
Flue-gas or exhaust-gas recirculation (EGR)	Recirculation of part of the flue-gas to the combustion chamber to replace part of the fresh combustion air, with the dual effect of cooling the temperature and limiting the O_2 content for nitrogen oxidation, thus limiting the NO_x generation. It implies the supply of flue-gas from the furnace into the flame to reduce the oxygen content and therefore the temperature of the flame. The use of special burners or other provisions is based on the internal recirculation of combustion gases which cool the root of the flames and reduce the oxygen content in the hottest part of the flames.	Boilers, turbines and engines
Fuel staging (FS)	The technique is based on the reduction of the flame temperature or localised hot spots by the creation of several combustion zones in the combustion chamber with different injection levels of fuel and air. The retrofit may be less efficient in smaller plants than in larger plants.	Boilers
Lean-burn concept and advanced lean-burn concept (LB)	The control of the peak flame temperature through lean-burn conditions is the primary combustion approach to limiting NO_x formation in gas engines. Lean combustion decreases the fuel to air ratio in the zones where NO_x is generated so that the peak flame temperature is less than the stoichiometric adiabatic flame temperature, therefore reducing thermal NO_x formation. The optimisation of this concept is called the 'advanced lean-burn concept'.	Gas engines
Low-NO_x burners (LNB)	The technique (including ultra- or advanced low-NO_x burners) is based on the principles of reducing peak flame temperatures; boiler burners are designed to delay but improve the combustion and increase the heat transfer (increased emissivity of the flame). The air/fuel mixing reduces the availability of oxygen and reduces the peak flame temperature, thus retarding the conversion of fuel-bound nitrogen to NO_x and the formation of thermal NO_x, while maintaining high combustion efficiency. It may be associated with a modified design of the furnace	Boilers

	combustion chamber. The design of ultra-low-NO_X burners (ULNBs) includes combustion staging (air/fuel) and firebox gases' recirculation (internal flue-gas recirculation). The performance of the technique may be influenced by the boiler design when retrofitting old plants.	
Low-NO_X combustion concept in diesel engines (engine tuning - ET)	The technique consists of a combination of internal engine modifications, e.g. combustion and fuel injection optimisation (the very late fuel injection timing in combination with early inlet air valve closing), turbocharging or Miller cycle.	Engines
Oxidation catalysts (OC)	The use of catalysts (that usually contain precious metals such as palladium or platinum) to oxidise carbon monoxide and unburnt hydrocarbons with oxygen to form CO_2 and water vapour. Not suitable for abatement of short chain alkanes CH_4, C_2H_6 and C_3H_8.	Engines and turbines
Reduction of the combustion air temperature (RAT)	The use of combustion air at ambient temperature. The combustion air is not preheated in a regenerative air preheater.	Gas turbines and boilers
Selective catalytic reduction (SCR)	Selective reduction of nitrogen oxides with ammonia or urea in the presence of a catalyst. The technique is based on the reduction of NOX to nitrogen in a catalytic bed by reaction with ammonia (in general aqueous solution) at an optimum operating temperature of around 300–450 °C. Several layers of catalyst may be applied. A higher NOX reduction is achieved with the use of several catalyst layers. The technique design can be modular, and special catalysts and/or preheating can be used to cope with low loads or with a wide flue-gas temperature window. 'In-duct' or 'slip' SCR is a technique that combines SNCR with downstream SCR which reduces the ammonia slip from the SNCR unit.	Gas turbines, engines and boilers
Selective non-catalytic reduction (SNCR)	Selective reduction of nitrogen oxides with ammonia or urea without a catalyst. The technique is based on the reduction of NO_X to nitrogen by reaction with ammonia or urea at a high temperature. The operating temperature window is maintained between 800 °C and 1 000 °C for optimal reaction. The use of the technique may lead to (slip) ammonia emissions.	Boilers, engines
Water/steam addition (WSA)	Water or steam is used as a diluent for reducing the combustion temperature in gas turbines, engines or boilers and thus the thermal NO_X formation. It is either premixed with the fuel prior to its combustion (fuel emulsion, humidification or saturation) or directly injected in the combustion chamber (water/steam injection).	Gas turbines, engines and boilers

(1) See Appendix 3 and section 5 of this document for a more complete set of applicability restrictions.

2.2.3.1 Specific features of technologies to reduce NOx for engines

There are a number of different engine types and designs; these are described in Appendix 5 of this document. The following table summarises how the MCPD addresses the different engines. There are also ELV exceptions (footnotes) for lower speed engines.

Table 2-5 MCPD coverage of different engine types

Feature	Value	Described in MCPD	Exemption
Principle	Gas engine: Otto cycle and uses spark ignition	Yes (including ignition approach)	

	Diesel engine: diesel cycle and uses compression ignition		Higher NOx ELV
	Dual fuel: Whilst dual fuel engines are running in liquid mode they operate according to the diesel cycle running in gas mode, they operate according to the Otto cycle but without the spark ignition		Higher NOx ELV
Size	1-5 MW_{th}	Disaggregated in MCP ELV tables	Higher NOx ELV
	5-20 MW_{th}		Higher NOx ELV

Engines design options are typically more diverse than turbines or boiler design options. This leads to wider emission performance and specific technologies to reduce emissions for each engine category. The Otto cycle differs from the diesel one and so does their ignition approach (compression or spark). Emission performance and abatement technologies do also vary depending on fuel, speed (rpms) and number of strokes.

There have been more recent developments with respect to reducing sizes for some emission abatement technologies, some aiming to help ships meet more stringent emissions regulations. For example, SCR and EGR systems are now smaller than in 2010. There are design features to reduce space requirements for SCRs. It is now possible to select a smaller high-pressure SCR (upstream turbine) for certain types of engines (some 2 stroke engines) or low-pressure SCR arrangement with implications in lay out (space requirements). There is a NOx reduction fund in Norway[3] (for the marine sector) that provides a list of suppliers for each NOx reduction option with a large list of references for fitting emission abatement devices in small ships.

Low NOx combustion concept in engines (also called Engine Tuning - ET) comprises a long list of internal engine optimisation modifications such as compression ratio, chamber shape modifications, air intake systems optimisations or Miller timing valve actuation.

The use of water to reduce peak combustion temperature (often called water/steam addition - WSA) comprises a wide set of different technologies based on the same principle. This include water fuel emulsions, injection of water or steam or intake air humidification.

2.2.4 Technologies to reduce SO_2 emissions

This section lists candidate best performing technologies that can reduce the emissions of SO_2 from MCPs. These are described in Table 2-6 below, additional information on each technology can be found in Appendix 3. Generic technologies mentioned in section 2.2.1, such as combustion optimisation, do also apply here.

Table 2-6 Candidate best available technologies to reduce emissions of SO_2 from MCPs

Candidate best available technology	Description	Most commonly used (1)
Boiler sorbent injection (in-furnace or in-bed) (BSI)	The direct injection of a dry sorbent into the combustion chamber, or the addition of magnesium- or calcium-based absorbents to the bed of a fluidised bed boiler. The surface of the sorbent particles reacts with the SO_2 in the flue-gas or in the fluidised bed boiler. It is mostly used in combination with a dust abatement technique.	CFB boilers (not in use in BFB nor grate boilers)

---

[3] https://www.nho.no/samarbeid/nox-fondet/the-nox-fund/articles/technologies-and-suppliers/

Semi dry scrubber (CFB)	Flue-gas from the boiler air preheater enters the CFB absorber at the bottom and flows vertically upwards through a Venturi section where a solid sorbent and water are injected separately into the flue-gas stream. It is mostly used in combination with a dust abatement technique.	Boilers and gas turbines
Duct sorbent injection (DSI)	The injection and dispersion of a dry powder sorbent in the flue-gas stream. The sorbent (e.g. sodium carbonate, sodium bicarbonate, hydrated lime) reacts with acid gases (e.g. the gaseous sulphur species and HCl) to form a solid which is removed with dust abatement techniques (bag filter or electrostatic precipitator). DSI is mostly used in combination with a bag filter.	Boilers and gas turbines
Seawater scrubber (SWS)	A specific non-regenerative type of wet scrubbing using the natural alkalinity of the seawater to absorb the acidic compounds in the flue-gas.	Boilers and gas turbines
Spray dry absorber (SDA)	A suspension/solution of an alkaline reagent is introduced and dispersed in the flue-gas stream. The material reacts with the gaseous sulphur species to form a solid which is removed with dust abatement techniques (bag filter or electrostatic precipitator). SDA is mostly used in combination with a bag filter.	Boilers
Flue gas condenser (GC)	A heat exchanger where water is preheated by the flue-gas before it is heated in the steam condenser. The vapour content in the flue-gas thus condenses as it is cooled by the heating water. The flue-gas condenser is used both to increase the energy efficiency of the combustion unit and to remove pollutants such as dust, SOx, HCl, and HF from the flue-gas.	CHP Boilers
Wet scrubbing (WS)	Use of a liquid, typically water or an aqueous solution, to capture the acidic compounds from the flue-gas by absorption. sulphur oxides are removed from flue-gases through various processes generally involving an alkaline sorbent for capturing gaseous SO_2 and transforming it into solids. In the wet scrubbing process, gaseous compounds are dissolved in a suitable liquid (water or alkaline solution). Simultaneous removal of solid and gaseous compounds may be achieved. Downstream of the wet scrubber, the flue-gases are saturated with water and separation of the droplets is required before discharging the flue-gases. The liquid resulting from the wet scrubbing is sent to a waste water treatment plant and the insoluble matter is collected by sedimentation or filtration	Gas turbines, engines and boilers

(1) See Appendix 3 and section 5 of this document for a more complete set of applicability restrictions.

2.2.5 Technologies to reduce dust emissions

This section lists candidate best available technologies that can reduce the emissions of dust from MCPs. These are described in Table 2-7 below, additional information on each technique can be found in Appendix 3. Generic techniques mentioned in section 2.2.1, such as combustion optimisation, do also apply here.

Table 2-7 Candidate best performing technologies to reduce emissions of dust from MCPs

Candidate best available technology	Description	Most commonly used (1)

Bag filter (BF)	Bag or fabric filters are constructed from porous woven or felted fabric through which gases are passed to remove particles. The use of a bag filter requires the selection of a fabric suitable for the characteristics of the flue-gas and the maximum operating temperature.	Gas turbines, engines and boilers
Ceramic Filter (CF)	In a ceramic filter the contaminated gas is led through the filtering material, in a process comparable to that of a fabric filter. The difference with a fabric filter is that the filtering material is ceramic. There are also designs where acidic compounds such as HCl, NO_X, SO_X and dioxins are removed. In such a case, the filtering material is fitted with catalysts and the injection of reagents may be necessary.	High temperature flue-gas applications.
Soot filter (SF)	A diesel particulate filter removes soot particles from the exhaust gas that are produced during the combustion process that takes place in the engine. This is done by directing the exhaust gas through filter substrate (different materials are used such as ceramic). Soot particles are deposited on the walls of the channels as the exhaust gas passes through the structure. There are different approaches to regenerate these devices.	Small size engines (<10MW)
Electrostatic precipitator (ESP)	Electrostatic precipitators operate such that particles are charged and separated under the influence of an electrical field. Electrostatic precipitators are capable of operating under a wide range of conditions. The abatement efficiency typically depends on the number of fields, the residence time (size), catalyst properties, and upstream particle removal devices. ESPs generally include between one and five fields. The most modern (high-performance) ESPs have up to seven fields.	Gas turbines, engines and boilers
Use of clean fuels (fuel choice-FC)	Choosing fuels with low Sulphur, Nitrogen and ash content.	
Flue gas condenser (GC)	A heat exchanger where water is preheated by the flue-gas before it is heated in the steam condenser. The vapour content in the flue-gas thus condenses as it is cooled by the heating water. The flue-gas condenser is used both to increase the energy efficiency of the combustion unit and to remove pollutants such as dust, SOx, HCl, and HF from the flue-gas.	CHP Boilers
Multicyclones (MC)	Set of dust control systems, based on centrifugal force, whereby particles are separated from the carrier gas, assembled in one or several enclosures.	Boilers
Wet scrubbing (WS)	Use of a liquid, typically water or an aqueous solution, to capture the acidic compounds from the flue-gas by absorption. sulphur oxides are removed from flue-gases through various processes generally involving an alkaline sorbent for capturing gaseous SO_2 and transforming it into solids. In the wet scrubbing process, gaseous compounds are dissolved in a suitable liquid (water or alkaline solution). Simultaneous removal of solid and gaseous compounds may be achieved. Downstream of the wet scrubber, the flue-gases are saturated with water and separation of the droplets is required before discharging the flue-gases. The liquid resulting from the wet scrubbing is sent to a waste water treatment plant and the insoluble matter is collected by sedimentation or filtration	Gas turbines, and boilers

(1) See Appendix 3 and section 5 of this document for a more complete set of applicability restrictions.

2.3 Emerging technologies applicable to MCPs

The following technologies have not yet been proven at commercial scale MCPs .

2.3.1 Technologies to maximise energy efficiency

There are a number of marginal developments on existing technologies to increase energy efficiency. These developments are supporting the continuous evolution of energy efficiency with time in almost all combustion plant categories. There are not so many disruptive technologies based on new or different scientific principles.

Table 2-8 Emerging technologies to increase energy efficiency for MCPs

Technology name	Two-stage turbocharging in large lean-burn engines
Description	A combination of the Miller cycle (early inlet valve closure timings before bottom dead centre (BDC)) and high-pressure turbocharging is used to reduce emissions of NO_X and, at the same time, lower fuel consumption and CO_2 emissions while achieving higher power density (increased unit output). For lean-burn-type gas engines the maximum cycle temperature is a limiting factor for the mean effective pressure and efficiency. The Miller cycle allows reduced combustion temperatures and thus higher compression ratios. Besides lower NO_X emissions this also results in lower fuel consumption.
Applicability restrictions	Applicable to engines burning liquid and gaseous fuels (still in R&D phase).
Reference documents:	Best Available Techniques (BAT) Reference Document for Large Combustion Plants, European Commission, 2017.

Technology name	Hygroscopic cycle
Description	Hygroscopic cycle is a thermodynamic cycle similar to Rankine cycle characterized by working with hygroscopic compounds, which optimize the condensation of the turbine exhaust steam, without need of cooling water for refrigeration. Hygroscopic compounds properties, in particular their higher condensation temperature at a given pressure, allow enhancing the condensation of the turbine exhaust steam in an absorber apparatus. In the hygroscopic cycle indeed a steam absorber replaces the exhaust steam condenser. In the absorber, the exhaust steam is put in direct contact with a liquid reflux stream, rich in hygroscopic compounds, thus forcing the absorption of steam on condensation nuclei. The whole exhaust steam is condensed inside the steam absorber. The benefits are increased energy efficiency and saving of water uptake.
Applicability restrictions	Applicable in any steam power plant independently of its power rate or location.
Reference documents:	• IMASA, Engineering and Projects, S.A., http://www.imasa.com/en/portal.do • Internal communication with DG environment (and EIPPCB)

Technology name	Lignite pre-drying in fluidized beds
Description	Most lignite fuels have moisture content of 50-65%. Flue gas recycling, and thereby a large part of the lignite energy content, is used to evaporate H2O

	before combustion, if no special back-up firing is installed. As this vapour remains in the flue gas, considerable energy losses occur. Extracting a large part of the moisture and removing it in liquid state before fuel injection into the burner enables higher energy recovery rates due to lower heat losses in the flue gas. • Recovering evaporation energy by condensing the moisture decreases net energy demand. Liquid coal water and dried lignite (moisture content can be around 10-15%) are process products. Mills, fuel feed and boiler layouts are different from conventional lignite combustion. Predrying can increase total plant efficiency by 4-5 percentage points
Applicability restrictions	Applicable to new lignite power plants of all sizes. May be suitable for existing plants, if only smaller proportions of fuel are predried. Predrying lignite may lead to a partial reduction of backup-firing needs and increase total plant efficiency
Reference documents:	• Emerging techniques and technologies for large combustion plants up to 500 MWth capacity (Ademe for Unece, 2012) • Techno-economics of modern pre-drying technologies for lignite-fired power plants (IEA clean coal centre, 2014) • Development status of WTA fluidized-bed drying for lignite at RWE Power A (Klutz, H., Moser, C. and Block, D, 2010).

2.3.2 Technologies to reduce NO_x

NOx emission reduction is probably one of the key environmental topics on combustion process research and developments. The majority of these novel technologies are applicable to a wide range of sizes (beyond 50 MW). There are also numerous technologies at lower stages of development (such as Plasma assisted catalytic reduction or Combustion Air Saturation System).

Table 2-9 Emerging technologies to reduce NOx emissions from MCPs

Technology name	Flameless Combustion
Description	The dilution of reactants achieved by a strong circulation of burnt gases achieves simultaneously very low NO_x emissions and high heating efficiency. The name of the technique derives from the fact that there is no visible flame. Emission figures below 50 mg/Nm^3 (at 3 % O_2) have been reported (without additional primary or secondary technologies).
Applicability restrictions	Desirable mode of combustion for gas turbines, as lean instabilities become more of a problem for higher pressure ratio engines. The implementation of flameless combustion has been successfully demonstrated in non-adiabatic type combustion systems, such as industrial furnaces. However, operational parameters for gas turbine combustors are very different from those of industrial furnaces, which possess several major challenges to applying flameless combustion to gas turbines. Burner retrofit should be generally applicable.

Reference documents:	• Ourliac et al., 'Projet CANOE – Clean flameless combustion boiler, Rapport final', Convention ADEME / GDF SUEZ / CORIA, 2015, / Ecole Centrale Paris #0974C0047 • Ourliac et al., 'MILD combustion for industrial boilers', 10th European Conference on Industrial Furnaces and Boilers conference (INFUB), 2015, Oporto (Portugal) • Stierlin et al., 'Combustion plants, natural gas and NO_X emissions: What is at stake in flameless combustion for NO_X Reduction', EFE Seminar on IED directive and its industrial impacts, 2011, Paris (France) • Stierlin, 'Flameless combustion in industrial boilers', 19th EGTEI Meeting, 2011, Rome (Italy) • Villermaux et al., 'GDF SUEZ activities on flameless combustion: from physical phenomena analysis to industrial-scale applications', International Gas Research Union Conference, 2008, Paris (France) • Levy et al., 'Basic thermodynamics of FLOXCOM, the low-NOx gas turbines adiabatic combustor', Applied Thermal Engineering, Vol. 24, 2004, pp. 1593 – 1605 • Milani et al., 'Flameless Oxidation Technology', 25th Event of the Italian Section of the Combustion Institute, 2002, Rome (Italy)

Technology name	Split cycle engine concept
Description	Engine concept that seeks to redefine the engine and its combustion process through the use of a recuperated split-cycle with isothermal compression. (In an isothermal process, the temperature is constant.) This concept is based on the use of a separate induction and compression cylinder from that used for combustion and exhaust. This enables recovery of otherwise wasted exhaust heat to the working gas after the end of compression. For highest efficiency, the compression process is carried out isothermally, cooled via the injection of a small amount of liquid nitrogen. There are various suppliers' developments: cryopower and Iso engine. The cryopower cycle and structure is very similar to that of the IsoEngine. However, the CryoPower engine is mainly targeted at heavy duty vehicles, such as long-haul trucks, whereas IsoEngine was designed for stationary power generation. ...)[4]
Applicability restrictions	Generally applicable to engines.
Reference documents:	• CryoPower webpage[5]. • A review of split-cycle engines, 2018

Technology name	Low-Temperature Oxidation (LTO)-LoTOx™
Description	The Low-Temperature Oxidation (LTO) is a process patented by Linde for NO_X removal. It is an end-of-pipe system which removes NO_X by the addition of ozone and thus oxidises the nitrogen oxides to N_2O_5 then can be removed by regular abatement equipment due to its high solubility (e.g. wet electrostatic precipitators).

---

[4] https://pdfs.semanticscholar.org/2c25/f53b7263553cdef4af4a0c6ed3085602172e.pdf?_ga=2.161732796.1294028279.1554882324-1503323054.1554882324

[5] https://ricardo.com/news-and-media/press-releases/ricardos-cryopower-demonstrates-high-efficiency-near-zero-emissions-heavy-duty-power

Applicability restrictions	Generally applicable.
Reference documents:	Linde LoTOx System[6]

Technology name	Catalytic ceramic bag filters
Description	Ceramic bag filters include an additional catalytic active layer on the inside of the filter bag. The catalyst itself is a standard SCR catalyst. NOx and dust contents are reduced.
Applicability restrictions	Generally applicable.
Reference documents:	• EGTEI, Emerging techniques and technologies for large combustion plants up to 500 MWth capacity, 2012. • Tri-Mer, production information on UltraCat ceramic filter systems, available at www.tri-mer.com (accessed Feb. 20th, 2019) • Ness, S., et. al.: “SCR Catalyst-Coated Fabric Filters for Simultaneous NOX and High-Temperature Particulate Control”, Env. Prog., 14 (1005) Issue 1, pp. 69-74.

Technology name	Low-swirl combustion of natural gas
Description	The LSC principle allows for ultra lean flames resulting in very low NOx levels. It has been specially developed for lean premixed fuels and operates at low swirl intensities, so that the flame does not recirculate. • A weak recirculation zone combined with a low residence time is used to allow for NOx low emissions. • Low NOx emission levels remain constant even in the case of high turndown ratios. NOx emissions at standard operating conditions were lower than 5 ppm-vol (at 15% O_2). Though residence time is reduced, CO emission levels are supposed to decrease, as turbulence in the centre of the flame is reduced, leading to full combustion.
Applicability restrictions	Applicability to plants with thermal outputs lower than 50 MWel has been proven. Current developments could extend the range up to 250 MWel. • The LSC is designed to be retrofittable, as fuel injectors are the main part to be replaced. No more information is available with regard to other substantial modifications which could be needed. • Currently applicable to boilers and gas turbines using lean premixed combustion of natural gas. Applicability is currently being extended to fuels with a high hydrogen content (with an aim to fire up to 90% H_2).

---

[6] https://www.linde-gas.com/en/images/LOTOX%20datasheet_tcm17-130449.pdf (accessed Feb, 20th 2019)

Reference documents:	• A comparison of the flow fields and emissions of high-swirl injectors and low-swirl injectors for lean premixed gas turbines, (Johnson, M. R. et al. Proceedings of the Combustion Institute, 2005). • Fundamental Issues of Lean Premixed H_2/air Combustion for Gas Turbine Development", (Cheng, Robert: DOE/EPRI Workshop on H2 Combustion in Gas Turbines, 2007). • Laboratory Investigations on Low-Swirl Injectors for IGCC Combustion Turbines (Cheng, Robert et al.: presented at ICEPAG 2008).

2.3.3 Multipollutant removal

Table 2-10 Emerging technologies to reduce multipollutant emissions from MCPs

Technology name	Electron beam flue gas treatment
Description	Dry scrubbing process to reduce the emissions of SO_2 and NO_X. The flue gas is irradiated resulting in the formation of ions and radicals. Those radicals react with ammonia, which is injected before irradiation, to the products $(NH_4)_2SO_4$ and NH_4NO_3 which are collected.
Applicability restrictions	Not identified
Reference documents:	• Yongxia Sun, Ewa Zwolińska & Andrzej G. Chmielewski (2015): Abatement Technologies for High Concentration of NO_X and SO_2 Removal from Exhaust Gases: a Review, Critical Reviews in Environmental Science and Technology, DOI: 10.1080/10643389.2015.1063334. http://dx.doi.org/10.1080/10643389.2015.1063334 • EGTEI, Emerging techniques and technologies for large combustion plants up to 500 MW_{th} capacity, 2012

Technology name	H_2 gas turbines
Description	Gas turbines, which are able to use pure hydrogen as a fuel or can shift between hydrogen-rich synthesis gas and pure hydrogen. Current research and development is based on natural gas/syngas f-class and g-class turbine technologies (up to 39% efficiency and up to 300 MWel), which are modified to fire hydrogen-rich or hydrogen only gas. In comparison to fuelling with methane or natural gas, the adiabatic flame temperature increases, therefore the combustion chamber, the injection ports and the turbine blades need to be improved. Furthermore, as the flame speed and specific flue gas volume increase, turbine layout needs to be changed in order to achieve maximum efficiencies. Environmental benefits: When pure hydrogen is used, only NOx emissions occur. According to manufacturers, NOx emissions as low as 2 ppm-vol (15% O_2) can be currently reached by diffusion flame combustion plus dilution or by reducing the combustion temperatures. In consequence, efficiency decreases in these cases. According to manufacturers, SOx and PM emissions would be close to zero. Therefore, no flue gas cleaning would be required and no subsequent residues (disposable filtered dusts, gypsum, etc) would be generated

Applicability restrictions	Retrofits are considered to be technically straight forward as simple turbine exchange and cast house modifications would be needed. However, it is important to highlight the fact that site specific issues are important in such cases, since the following parameters must be taken into account to reach the abovementioned emission targets: air intake system, feedstock pre-cleaning techniques, feedstock make-up, generator shaft, turbine housing. If retrofitted in combination with a fuel switch from CH_4 to H_2, infrastructure for H_2 supply/H_2 buffer tanks have to be constructed
Reference documents:	• Emerging techniques and technologies for large combustion plants up to 500 MWth capacity (Ademe for Unece, 2012) • Advanced Hydrogen Turbine Development Program of US DOE

3 Medium Combustion Plants performance

3.1 EU plant capabilities based on questionnaires

3.1.1 Introduction

This section summarises the analysis of the MCP questionnaire data. It presents the emissions figures of each individual fuel - combustion - pollutant combination. For the emissions data (excluding energy efficiency), there are 68 combinations to analyse, though only 32 of these have 6 or more sample points, which is agreed to be considered the threshold of plants needed for a full analysis in Sections 3.1.4 through 3.1.9. For energy efficiency, 8 out of 17 meet this threshold. Table 3-1 shows two characteristics about the dataset:

- Firstly, the sample size column is the initial sample size as measured by number of received questionnaires per plant-fuel category.
- Secondly, the pollutant-specific figures are the sample sizes after initial data cleaning and identification of usable data.

Samples that are not in bold in Table 3-1 have not been included in the following sub sections. The sample size is not large enough for meaningful inference. These small samples have been summarised in Appendix 1. Finally, it should be noted that any multi-fuel plant that uses only one type of fuel for > 90% of its total thermal fuel input, is placed into that fuel category. Of 35 engines and boilers that indicated to use multiple fuels, all but 2 plants have been re-categorised either through the threshold of 90%, or because they only used variations of another fuel category (different types of solid biomass, other gaseous or other liquid fuel).

Table 3-1 Summary of sample sizes across the 17 categories

Category	Fuel	Type	MCP sample size	MCPs with data on each environmental parameter				
				dust	SO_2	NO_x	CO	Energy Efficiency
1	Solid biomass	Boiler	53	**47**	**25**	**51**	**45**	**32**
2	Other solid fuel	Boiler	13	**12**	**13**	**13**	**7**	**11**
3	Gas oil	Boiler	4	3	3	3	3	3
4	Gas oil	Reciprocating Engine	10	**6**	**6**	**7**	**7**	**8**
5	Gas oil	Gas Turbine	2	2	2	2	2	2
6	Other liquid fuel	Boiler	2	1	1	1	2	2
7	Other liquid fuel	Reciprocating Engine	6	**6**	**6**	**6**	**6**	**6**
8	Other liquid fuel	Gas Turbine	0	0	0	0	0	0
9	Multifuel	Boiler	2	2	1	2	1	1
10	Multifuel	Reciprocating Engine	0	0				
11	Multifuel	Gas Turbine	0	0				
12	Natural Gas	Boiler	97	**13**	**16**	**74**	**46**	**48**
13	Natural Gas	Reciprocating Engine	35	5	**13**	**33**	**22**	**27**
14	Natural Gas	Gas Turbine	27	1	4	**21**	**16**	**12**
15	Other gaseous fuel	Boiler	19	6	8	**14**	**13**	5
16	Other gaseous fuel	Gas Turbine	0	0				

Category	Fuel	Type	MCP sample size	MCPs with data on each environmental parameter				
				dust	SO_2	NO_X	CO	Energy Efficiency
17	Other gaseous fuel	Reciprocating Engine	11	1	**6**	**10**	**10**	**11**
Total			**281**	**105**	**104**	**237**	**180**	**168**

3.1.2 Emissions methodology

Emission data shown here was standardised for an O_2 content of 6% for MCPs using solid fuels, 3% for MCPs, other than engines and gas turbines, using liquid and gaseous fuels and 15% for engines and gas turbines (similar to the ELVs in the MCPD). There are 7 steps to the data analysis of the 32 large sample 'combustion + fuel + pollutant' combinations. Firstly, the data is visualized according to its average emissions levels in step 1 to 3:

- **Step 1 Data cleaning:** to obtain a single sample for each analysis exercise, the data is cleaned through the following steps:
  - **I. Unreported information:** Many plants do not report data on one or more pollutants. This can be for good reason, such as dust emissions for Natural Gas which are not generally expected, but can also be for unexplained reasons, as it is for example expected for all plants to report on NOx emissions. Data is analysed per pollutant: when average value was not reported the information from that MCP has not been used.
  - **II. Consistency:** All emission figures are checked for consistency between their average, minimum and maximum values. In cases where these are not consistent as expected (average equal to 0 while the maximum is non-zero, for example) the data point is not used. Furthermore, emissions data is corrected to match the oxygen content of the fuel in the corresponding MCPD ELV. A caveat here is that emissions measurements use different averaging periods across the sample, but data has not been excluded based on this due to the already limited data available.
  - **III. Outliers:** Outliers are identified through the initial screening of each emissions cascade (starting with Figure 2-1). No analysis results (such as identifying best performers) have been produced with data including these outliers, but they are still visible in the cascade figures.
- **Step 2 Visualise average value performance:** The second step in the analysis uses a cascade representation that orders all plants in a plant-combustion category from low to high emissions. This step corrects for erroneous data (steps I and II of data cleaning) but does not yet remove outliers. Those are only removed during step 2. The available minimum and maximum values will be shown in the figure to capture variability. Alternatively, if a category does not have many minimum and maximum values (because operators have not filled in this field), p5 and p95 values are used to represent variability of the environmental performance.
- **Step 3 Visualise emission reduction technologies:** The third step involves visualising the technologies used by plants as markers on the figure produced in step 1. The technologies that are present from the best performing plants are identified. The 25th percentile and below of best performing plants are used to determine what technologies are employed by the 25% best performing plants. Outliers identified during data cleaning are not used for determining this range.

The following two steps include the analysis of what root causes could explain the variation observed in the emissions data. This is visualised as a grid of 4 to 6 scatter figures (such as in Figure 2-2), each exploring the correlation of a variable with emissions. These figures are available in Appendix 1 and 2.

- **Step 4 Root cause analysis –:** SIS/MIS and plant age, load factor and plant size Using a correlation coefficient as well as a visual inspection, each plant + combustion + pollutant combination with sufficient data points (>6) has been checked for a potential relationship of emissions with plants being in small isolated systems (SIS), medium isolated systems (MIS) and/or with the age of the plants. In terms of plant age, specific attention has been given to those plants from 2016 or later, as these are designated as 'new plants'. This analysis step also introduced the load factor during measurements (also known as the Full Load Operating Factor during measurements in %) and plant size.

  Note that the terminology used in the report for "new plants" differs from the same term used in the MCPD. Only 5 out of 17 categories have plants built in 2016 or later, with a total of 20 new plants.
- **Step 5 Root cause analysis – Load factor and plant size:** The fifth step continuing the root cause analysis introduces load factor (also known as the Full Load Operating Factor in %) and plant size and checks for potential correlation with emissions.

Finally, Steps 6 and 7 looked at the full dataset for a plant type and looks for correlations between some pollutants and the load factor and fuel characteristics.

- **Step 6 Correlation of NO_x, CO and load factor:** A review has been undertaken in each different plant category of the potential correlation of NOx emissions, CO emission and load factors (e.g. Pearson with R^2 >0.6) [7]. One would expect that plant operating with minimum NOx emissions would not achieve minimum CO emissions and vice versa, and that CO and NOx emissions are higher at lower load factors.
- **Step 7 Fuel composition:** When data was available on fuel composition, this has been compared with emission values e.g. Nitrogen, moisture content or sulphur content in fuel.

The following sections show the spread of emissions in a figure and summarise only the conclusions of the analysis steps one through five, including observations on the spread in the data, common technologies used, and any evidence of a relationship from the root cause analysis. This section does not display the correlations used and does not display the full summary statistics for each data analysis group. For this, please refer to the full analysis in Appendix 1.

Due to the limited number of reference plants data sets (283) the performance for emergency or backup units (e.g. < 500h/y) and less common fuels (e.g. straw, process gases, etc.) could not be assessed thoroughly in this section 3.1. Most data sets were provided by plants operating >70% load but Appendix 1 contain details on data provided for plants also at lower rates. In most cases the data indicates that % load does not have a clear impact on emissions performance.

Note: It is strongly recommended to use the files included in Appendix 1 to have a complete and precise review of the data. These html files in Appendix 1 allow visualisation of technology combinations. Due to high density of plants and other features, the figures included in the main body of this report may hide some information such as multiple technologies in use. The appendix also identifies, for each plant, the applicable MCPD emission limit value(s), including exceptions, that apply to that plant (if any).

---

[7] The Pearson correlation coefficient (R^2) is a measure of the linear correlation between two variables, such as plant age and emissions. In this study, a coefficient of 0.2 or more warrants further investigation of the data, and 0.5 or more is considered meaningful.

3.1.3 Energy efficiency methodology

This analysis uses an approach agreed for the LCP BREF review whereby energy efficiency is defined as the ratio between the net produced energy (electricity, hot water, steam, mechanical energy produced minus the imported electrical and/or thermal energy, e.g. for auxiliary systems' consumption) and the fuel energy input (as the fuel lower heating value) at the combustion unit boundary over a given period of time. This approach enables a comparison of energy efficiencies for different arrangements (e.g. such as CHP or combined cycles) and is called ‘fuel utilisation’.

For energy efficiency, Steps 1 - 6 of the data analysis approach is repeated. There are no specific technologies associated with energy efficiency in the questionnaire data, and there are also no ‘limit values’ available either. Instead, the focus is on comparing design efficiency (where available) to measured efficiency, and a root cause analysis to understand the variation in the data. See the full energy analysis in Appendix 2 for a specific breakdown of the analysis steps adapted for energy.

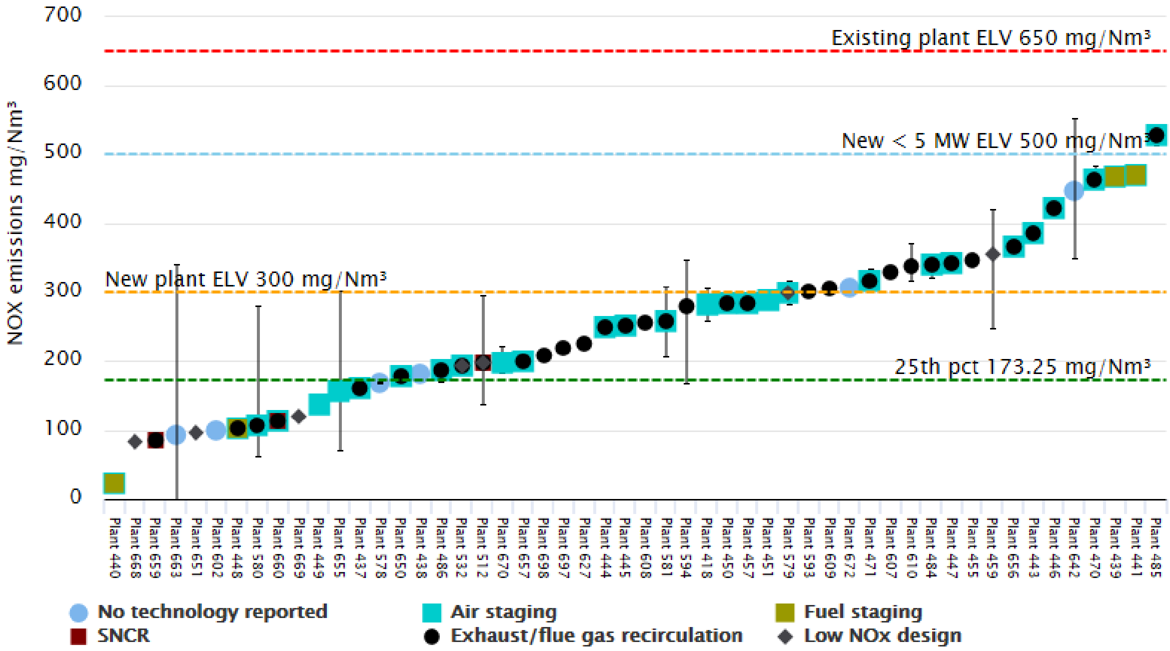
As a proxy for energy efficiency, the ‘total fuel utilisation’ is used. This is the most commonly available data point from both measured and design data, at 196 / 283 observations, and combines the output efficiency of thermal, electrical and mechanical energy. Other relevant data points, such as electrical efficiency are also reported in figures, where available, to facilitate comparison with different plant arrangements. Design efficiency data is also provided when available.

3.1.4 Solid biomass

3.1.4.1 NOx emissions from solid biomass boilers

As shown in Figure 3-1, 100% of these MCPs meets the limit value for existing plants, and 64% of them meet the ELV for new plants (300 mg/Nm³). A number of technologies and their combinations are employed for NO_x reduction by solid biomass boilers. Of these, Air staging, SNCR (selective non-catalytic reduction), Fuel staging, Exhaust/flue gas recirculation and Low NOx design are technologies applied by the 25% best performing plants at less than 173 mg/Nm³. No MCP reported used of SCR.

Figure 3-1 NO_x emissions from solid biomass boilers



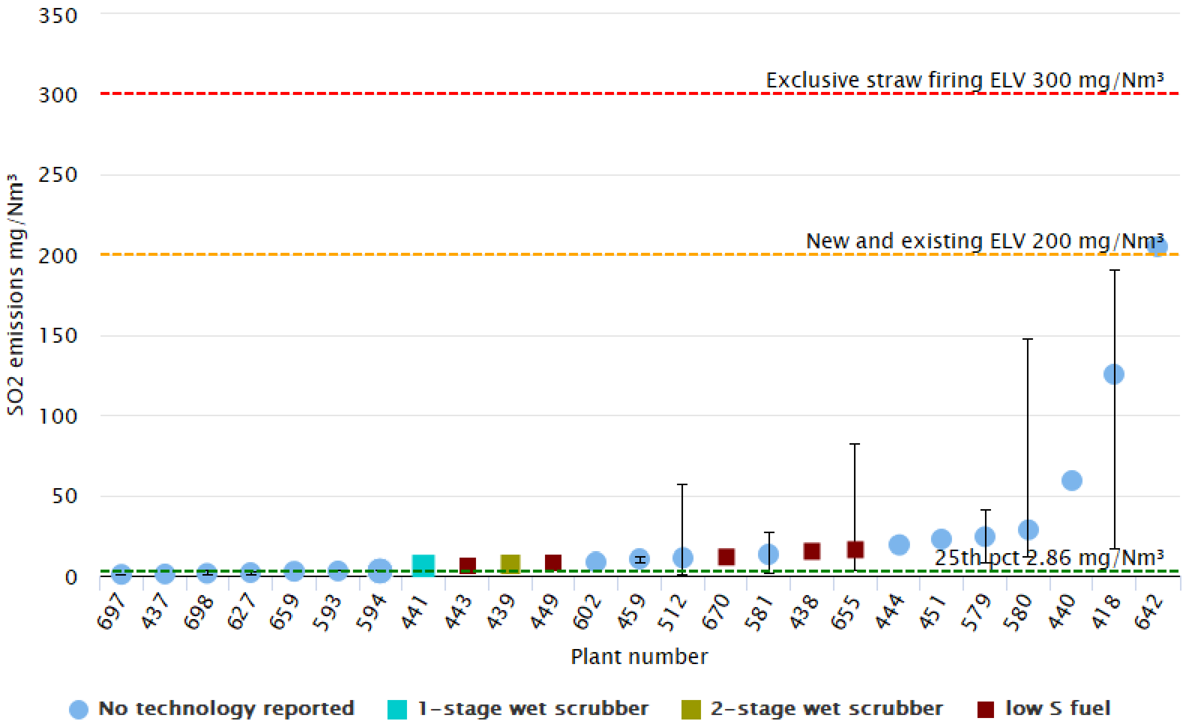
* Note, see Appendix 1 to view new plants, and to view a more detailed interactive graph of each technology category. This applies to all of the following sub-sections in section 3.1.

The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with plant age, rate nor size. The majority of large plants (>30MWth) are below 300 mg/Nm^3 but correlation with size is not robust. There is one SIS/MIS plant in this category. There is also no clear correlation of NOx emissions with nitrogen or moisture content in the fuel.

3.1.4.2 SO_2 emissions from solid biomass boilers

As shown in Figure 3-2, in this category the ELVs for new and existing plants are the same at 200 mg/Nm³ (not applicable to woody biomass fuels). Most of plants meet this limit value (excluding one outlier). No use of abatement technologies was reported by plants in the 25% best performing plants (2.9 mg/Nm³). No best performers were reported to be using cleaner fuels with low sulphur content.

Figure 3-2 SO_2 emissions from solid biomass boilers

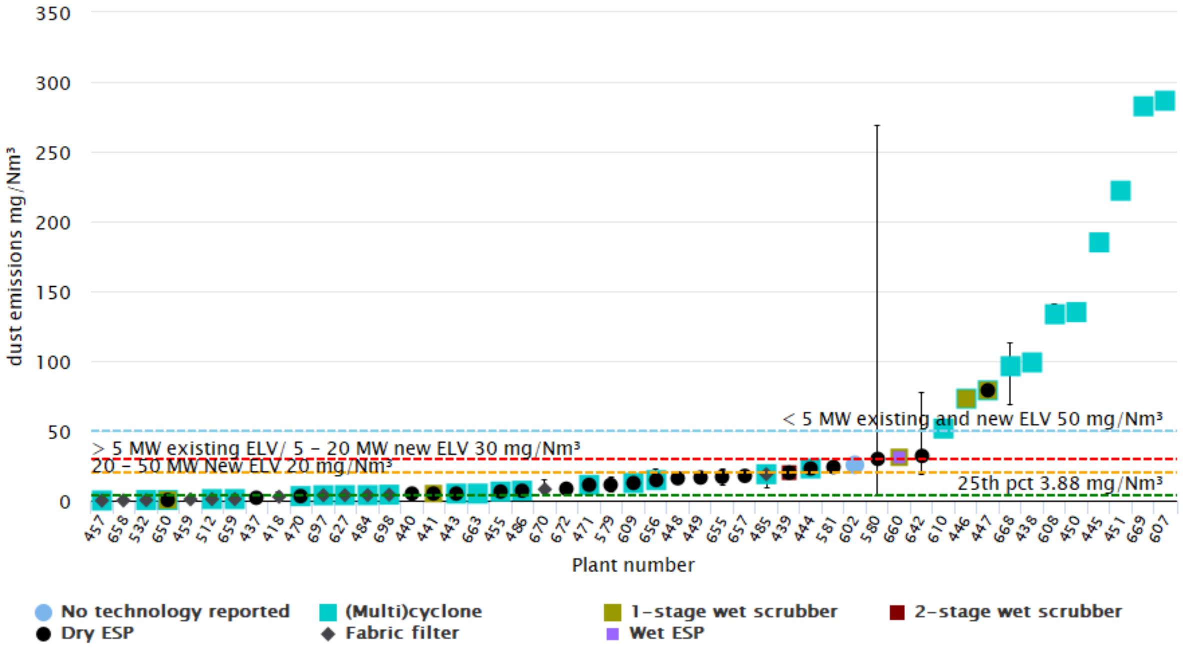


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of plant age, rate or size. As would be expected, plants burning fuels with higher sulphur content are leading to higher SO_2 emissions (with the exception of plant #441 which is using a wet scrubber).

3.1.4.3 Dust emissions from solid biomass boilers

As shown in Figure 3-3, for dust, around 70% of plants meets the limit value for existing plants, and 67% meet the value for new plants. Five technologies are employed for dust by the solid biomass boiler plants. Of these, multicyclone, scrubber, dry ESP and fabric filters are technologies used by the 25% best performing plants.

Figure 3-3 Dust emissions from solid biomass boilers

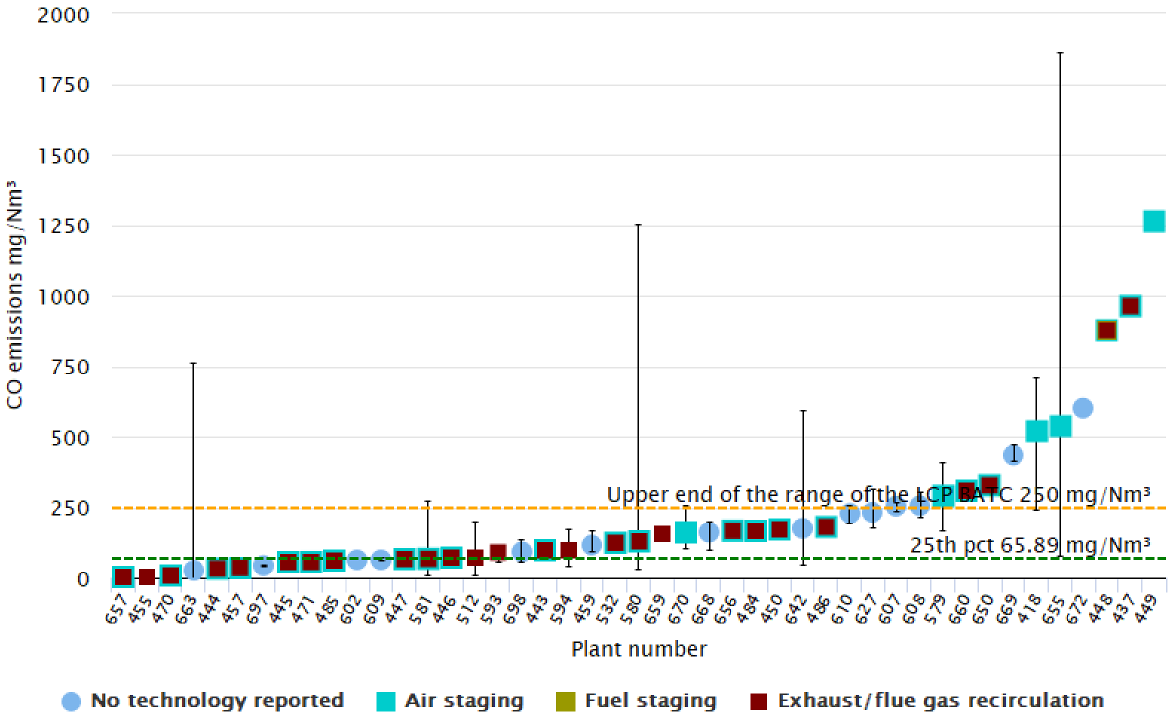


Similar to NO_x and SO_2 for solid biomass boilers, the root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of plant age, rate or size. Regarding plant size, a trend is observed showing better performance for larger (MWth) plants. MCPs using fuel with higher moisture content seem to have larger emissions of dust (see appendix 1 of this document).

3.1.4.4 CO emissions from solid biomass boilers

For CO there are no ELVs in the MCPD, so the upper end of the range of the indicative values from the LCP BAT conclusions is displayed instead. Around 72% perform below this value. Three technologies are used by the solid biomass boiler plants. Of these, air staging and exhaust/flue gas recirculation is used by the 25% best performing plants.

Figure 3-4 CO emissions from solid biomass boilers

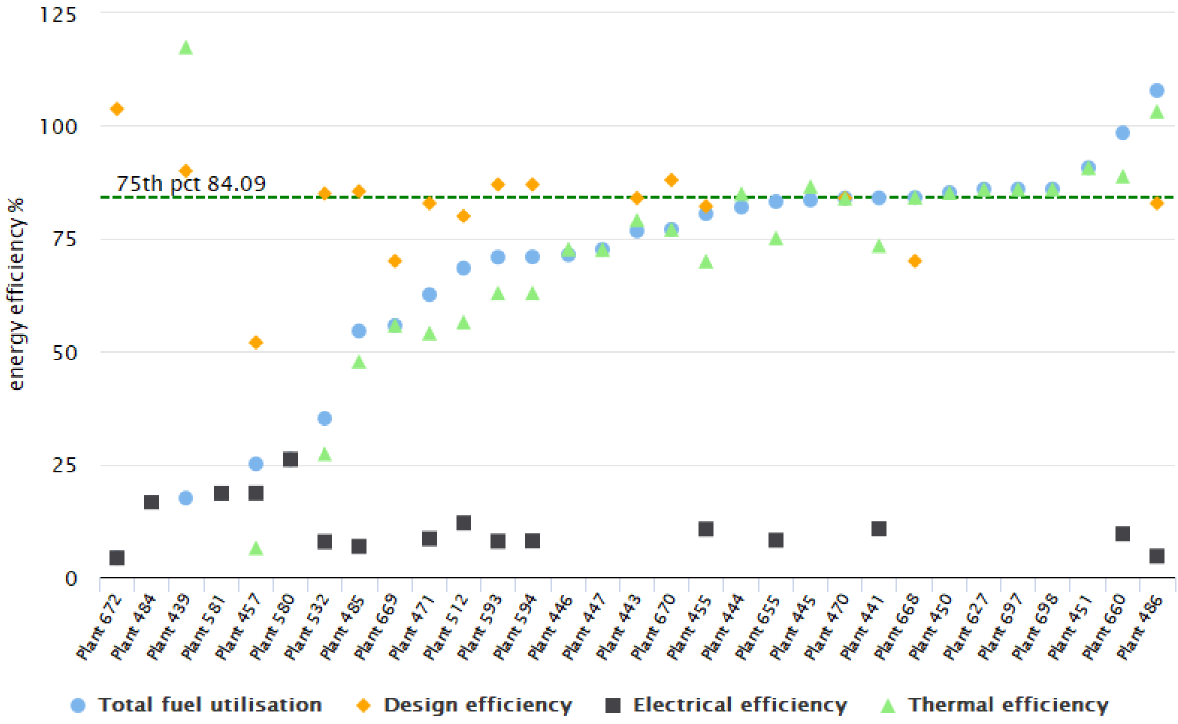


Similar to the other pollutants for solid biomass boilers, the root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of plant age, rate or size. Fuel moisture shows a weak correlation with CO emissions: see Appendix 1.

3.1.4.5 Energy efficiency of solid biomass boilers

Figure 3-5 shows the energy efficiency of solid biomass boilers. The 75th percentile value lies around 84% total fuel utilisation. CHP plants are reporting with around 10% electrical efficiency and 74% heat efficiency. Plant #486, with the highest value, is using a flue-gas condenser.

Figure 3-5 Energy efficiency of solid biomass boilers



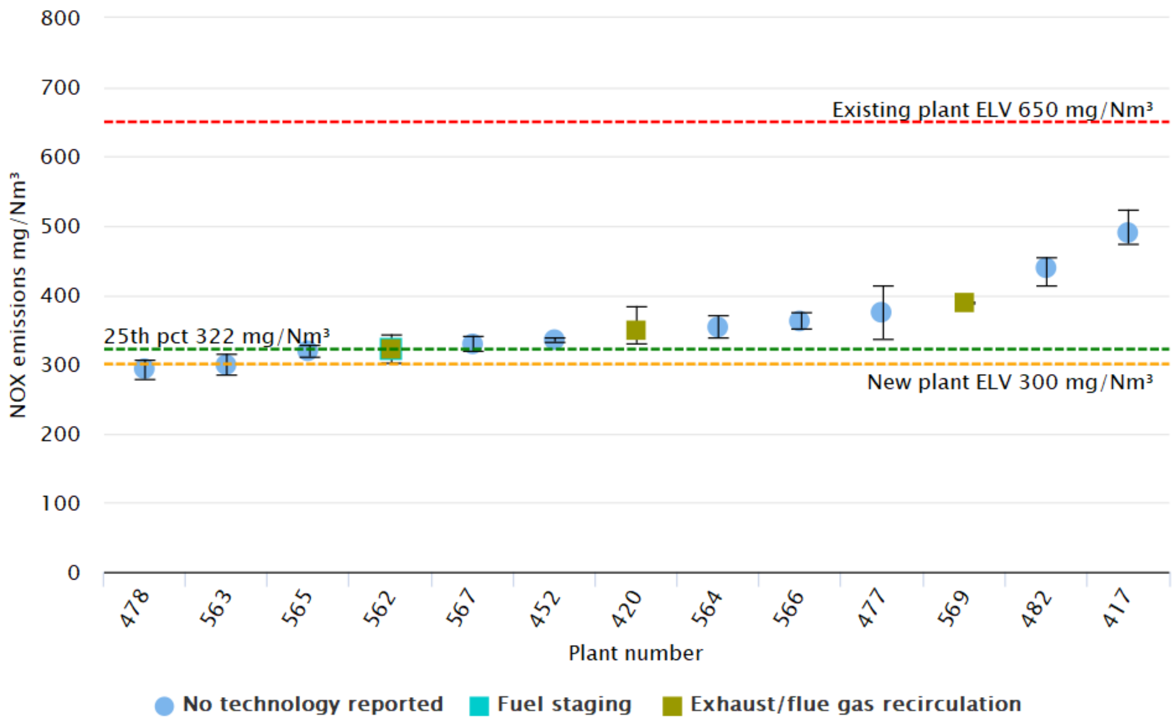
From a root cause perspective, the reported data includes a number of plants with low total fuel utilisation that are reported to operate at 100% load (which refers to how close the plant is operating to its capacity in terms of direct output). High load values do not appear to ensure the highest efficiencies. It is not clear from the data or plant details why this should be the case. See the full energy analysis in Appendix 2 for further details.

3.1.5 Performance of plants using other solid fuels

3.1.5.1 NOx emissions from other solid fuel boilers

Figure **3-6** shows the NO_x emissions of other solid fuel boilers. 100% of plants meet the limit value for existing plants, yet only 15% meet the value for new plants. Two technologies are employed for NO_x (fuel staging, exhaust/flue gas recirculation) both fuel staging (plant#562) and exhaust/flue gas recirculation are applied by the 25% best performing plants at less than ~ 322 mg/Nm^3 NO_x.

Figure 3-6 **NO_x emissions from other solid fuel boilers**

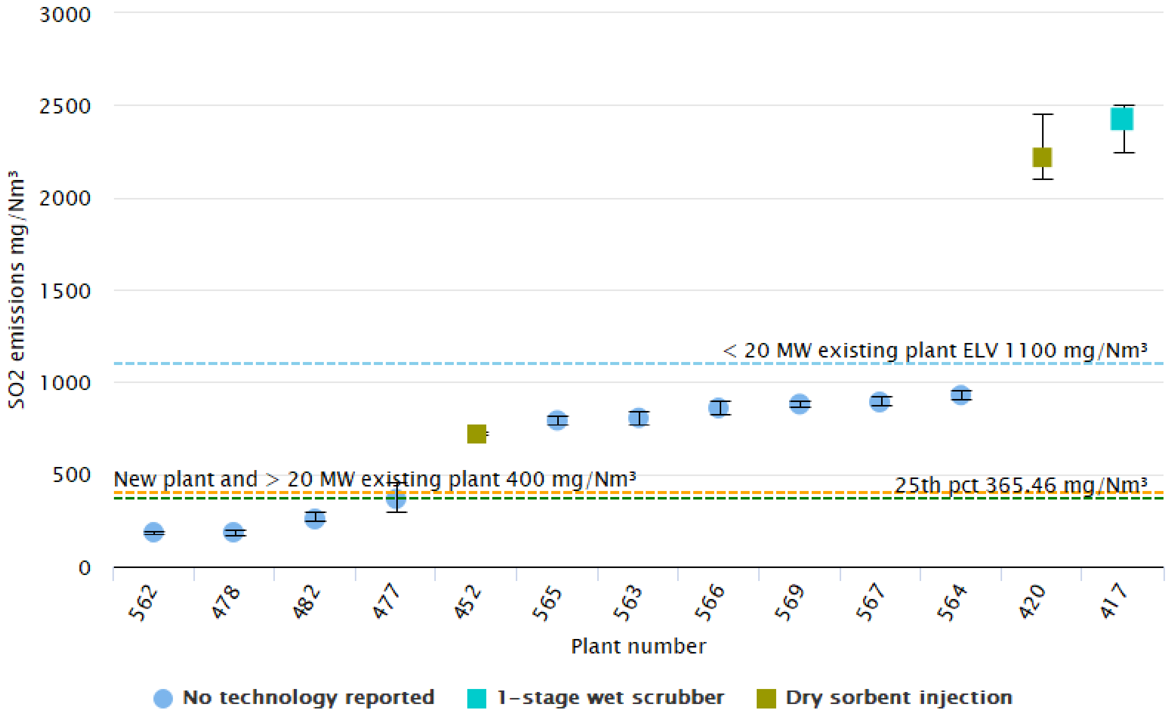


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of plant age, rate or size. There is one SIS/MIS plant in this category, which did not show to be significantly different from the average plant in performance, emitting 322 mg/Nm^3. Only one plant provided nitrogen content of fuel (so insufficient data to analyse) and correlation with fuel moisture is not robust.

3.1.5.2 SO_2 emissions from other solid fuel boilers

Figure 3-7 shows the SO_2 emissions of other solid fuel boilers. The ELVs for new plants is 400 mg/Nm^3 which can be met by 36% of plants, and 1100 mg/Nm^3 for existing plants which is met by 85% of plants. Two abatement technologies are employed for SO_2 by the other solid fuel boiler plants. Of these, none were reported to be used by plants in the 25% best performing plants.

Figure 3-7 SO_2 emissions from other solid fuel boilers

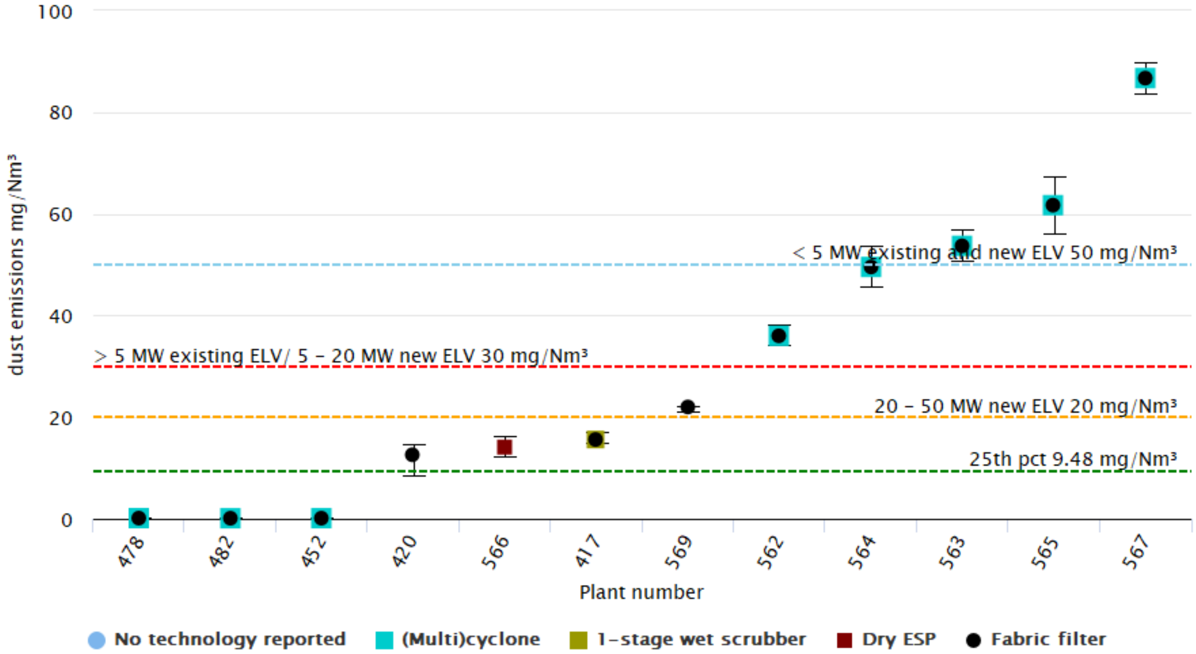


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of plant age, rate or size. The two SIS/MIS plants in this category have very low emissions of 6 and 187 mg/Nm^3 respectively, which is far below the 25th percentile mark of 238 mg/Nm^3. However, there is not sufficient evidence to indicate that SIS/MIS plants are performing different from the rest. There is not enough variation in the fuel sulphur data to demonstrate the expected linear relationship between fuel S content and emissions. See Figure 2-16 in Appendix 1 for more details.

3.1.5.3 Dust emissions from other solid fuel boilers

For dust, around 75% meets the limit value for existing plants, and 50% meets the value for new plants. Four technologies including scrubbers (plant#417) are employed for dust by the solid fuel boiler plants. Of these, fabric filters and multi-cyclones are technologies used by the 25% best performing plants.

Figure 3-8 Dust emissions from other solid fuel boilers

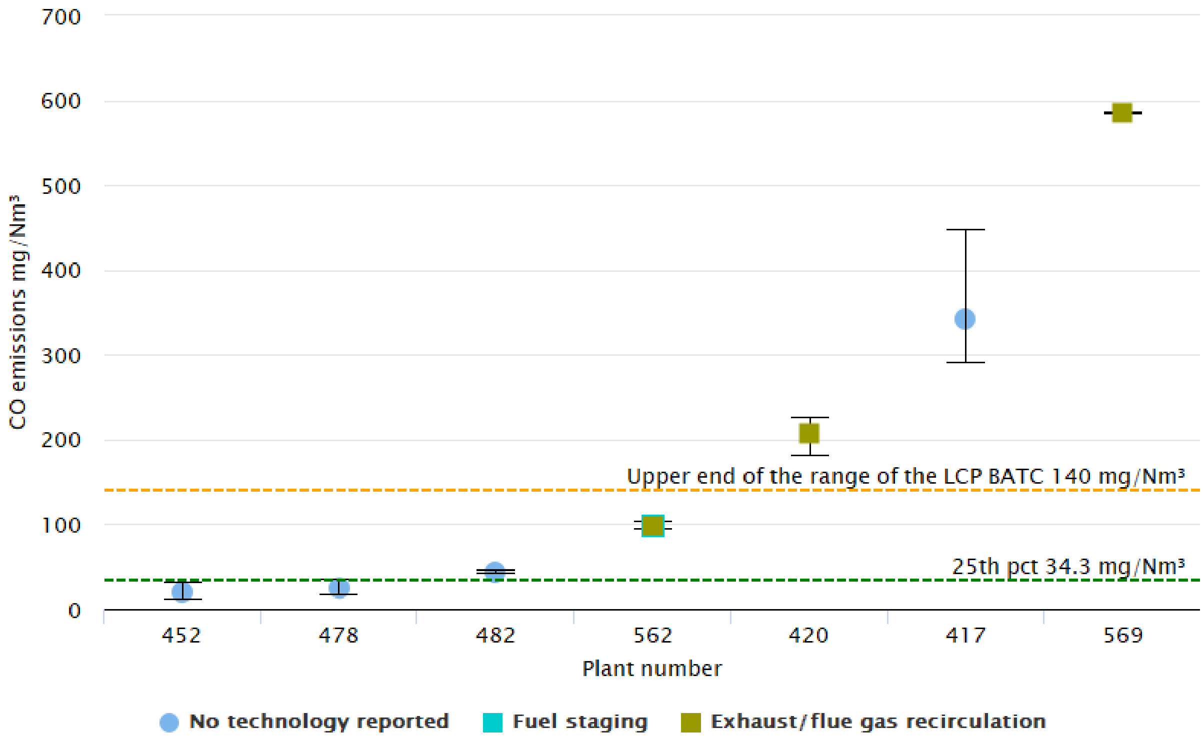


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of plant age, rate or size. There is a trend showing better performance in new plants and bigger MCPs but data is scarce (plant age) and correlation coefficient not robust (plant size). Data on fuel composition is not delivering sounds correlations with emissions (e.g. most having 10% moisture).

3.1.5.4 CO emissions from other solid fuel boilers

For CO there are no ELVs in the MCPD, so the upper end of the range of the indicative values from the LCP BAT conclusions is displayed instead. Around 63% perform below this value. Two technologies, exhaust/flue gas recirculation and fuel staging, are used by the other solid fuel boiler plants, none were reported by the 25% best performing plants.

Figure 3-9 CO emissions from other solid fuel boilers

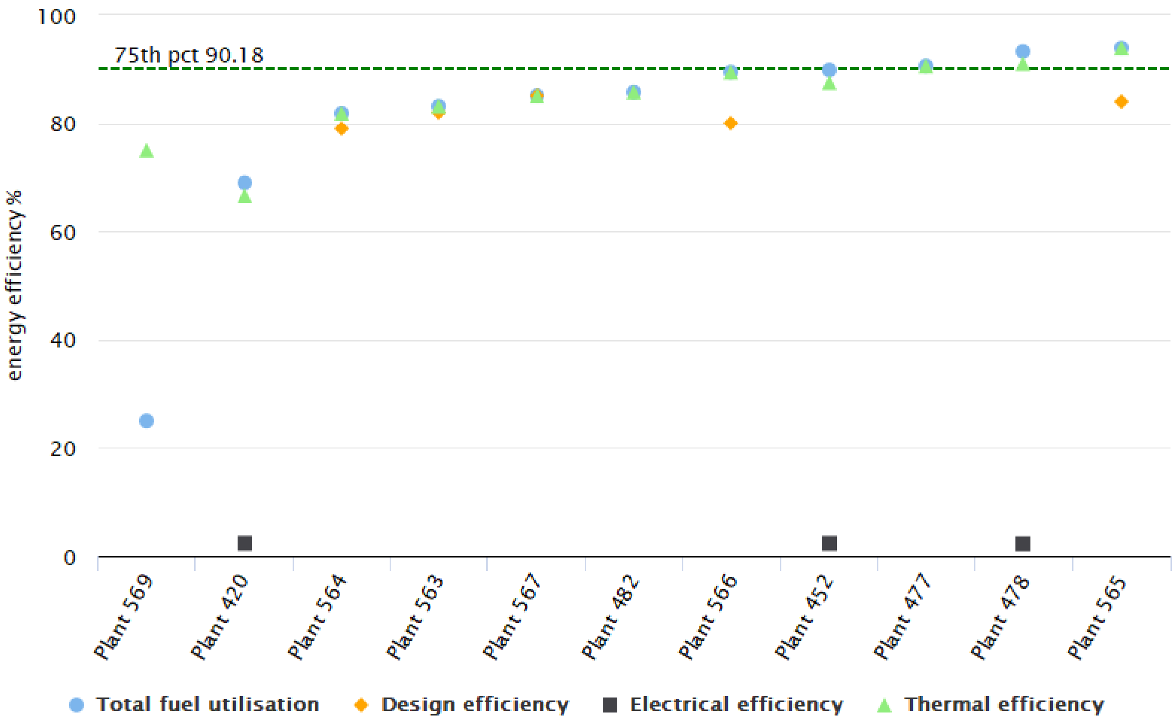


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of load factor, size or fuel composition. New plants seem to perform better but there are only four data points to underpin this statement.

3.1.5.5 Energy efficiency of other solid fuel boilers

Figure 3-10 shows the energy efficiency of other solid fuel boilers. The 75th percentile value lies at 90% total fuel utilisation. The variation is small, and no plants are displaying low performance. CHP plants are delivering around 2.3% electrical efficiency, so that their largest contribution to overall fuel usage comes from thermal efficiencies.

Figure 3-10 Energy efficiency of other solid fuel boilers



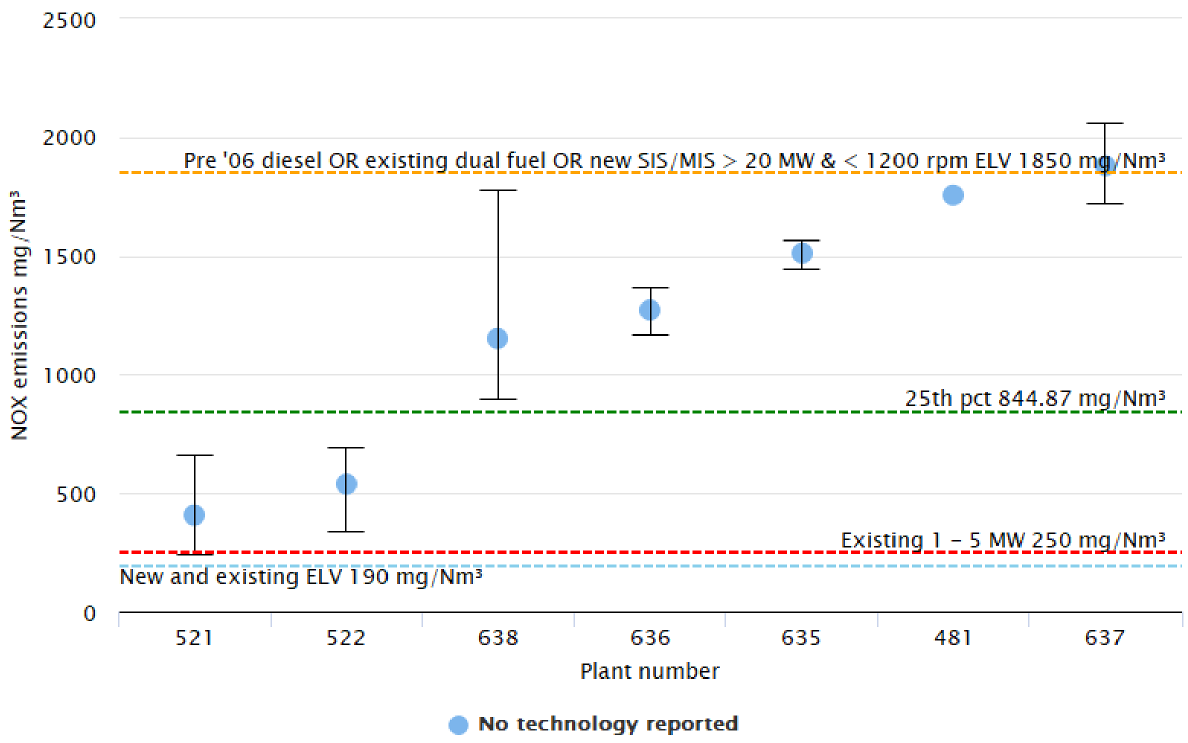
No conclusive evidence on any relationship between load factor, size and age could be found. One of the lowest efficiencies is achieved by the oldest plant (but data on plant age was available only for four MCPs).

3.1.6 Performance of plants using gas oil

3.1.6.1 NO_x emissions from gas oil engines

Figure 3-11 shows the NO_x emissions of gas oil reciprocating engines. There is an important ELV exception for this category at 1850 mg/Nm^3, which applies to plants that meet certain conditions[8]. This ELV exemption is significantly higher than the ELV value for new and existing plants at 190 mg/Nm^3. 86% (6 out of 7) of plants meet the SIS/MIS ELV for diesel engines the construction of which commenced before 18 May 2006 or for dual engines in liquid mode

Figure 3-11 NO_x emissions from gas oil engines



No abatement technologies are reported to be employed by these plants to reduce NO_x emissions. Plants #521, #522 and #481 are high-speed compression ignition engines. Plant #636 is the only low speed (<1200 rpm) engine; see appendix 1 for more details on engine types. Best performers in NOx emission do not have high CO emissions: this means that best NOx values are not achieved with major drawbacks in other emissions.

The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of plant age, rate or size; see Appendix 1 of this document for more details. All plants in this category are part of SIS/MIS, so no comparison can be done with non-SIS/MIS plants, which also applies to the analyses of dust, SO_2 and CO in the following sections. The limit value for non-SIS/MIS plants is much lower at 190 mg/Nm^3 and 200 mg/Nm^3 respectively, and no plant among the 7 in the survey meet that limit. There is no clear correlation between emission levels and nitrogen content of the fuel.

---

[8] MCPD, Annex II, part 2, footnote 4: “Until 1 January 2025 in SIS and MIS, 1 850 mg/Nm3 for dual fuel engines in liquid mode and 380 mg/Nm3 in gas mode; 1 300 mg/Nm3 for diesel engines with ≤ 1 200 rpm with a total rated thermal input less than or equal to 20 MW and 1 850 mg/Nm3 for diesel engines with a total rated thermal input greater than 20 MW; 750 mg/Nm3 for diesel engines with > 1 200 rpm.”

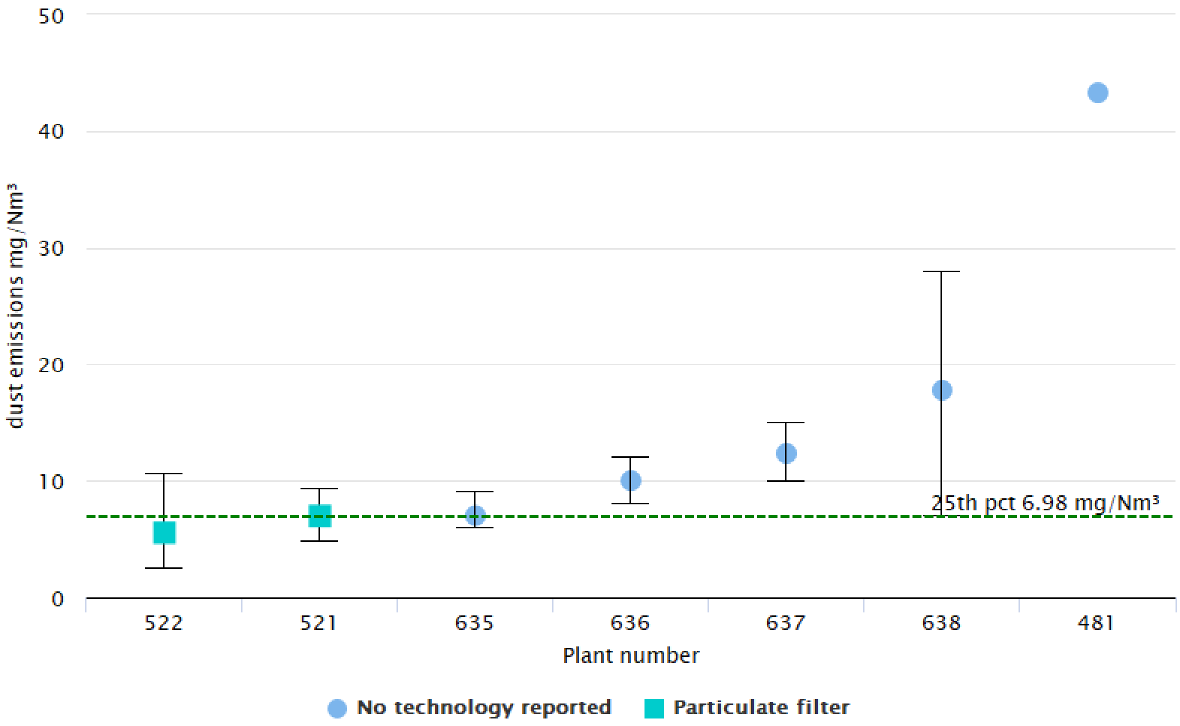
Existing medium combustion plants which are part of SIS or MIS shall comply with the emission limit values set out in Tables 1, 2 and 3 of Part 1 of Annex II from 1 January 2030.

An analysis has been carried out to compare gas oil engine NO_x emissions from before and after 2006. Please see section 3.1.7.1 for the analysis, which has been done together with the data from other liquid fuel engines.

3.1.6.2 Dust emissions from gas oil engines

Figure 3-12 shows the dust emissions of gas oil reciprocating engines. No dust ELV is available in the MCPD for this plant-fuel-emissions category. The lowest values are achieved by plants using particulate filters (DPF).

Figure 3-12 Dust emissions from gas oil engines

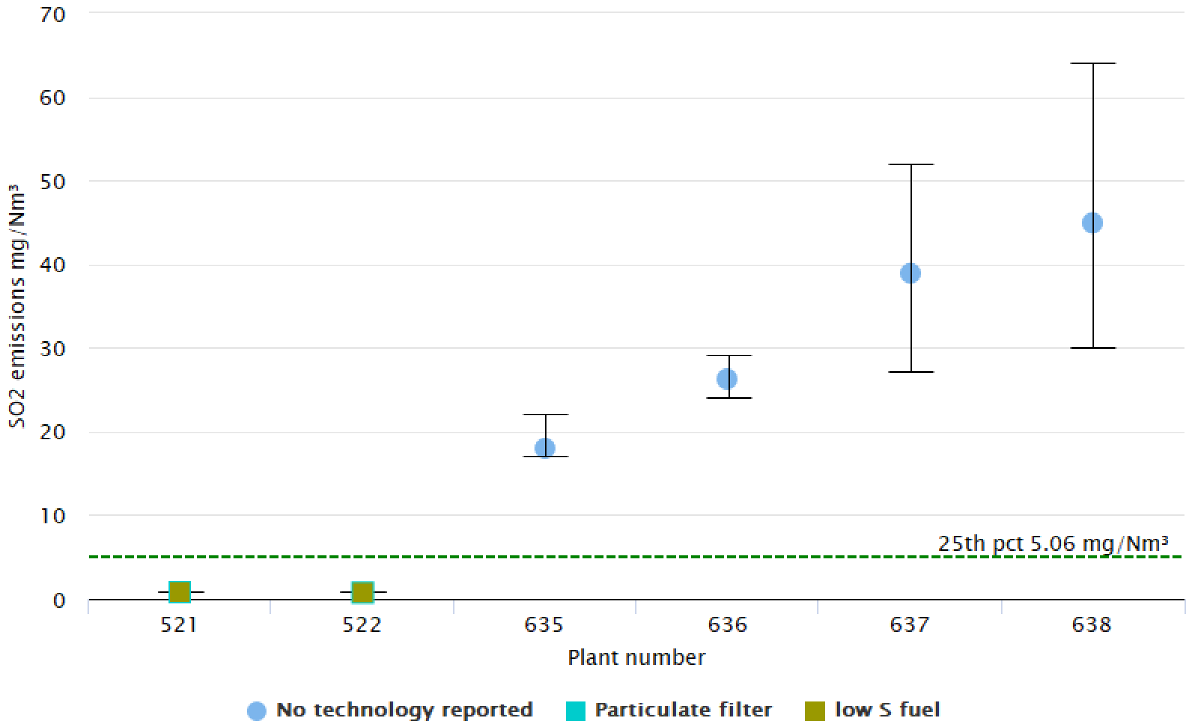


Like the NO$_x$ data for this plant-fuel-pollutant category, the root cause analysis (Steps 4 and 5) conclusions are similarly inconclusive. A small trend is seen with plant size, where larger plants are emitting more dust, but few data points support this conclusion.

3.1.6.3 SO_2 emissions from gas oil engines

Figure 3-13 shows the SO_2 emissions of gas oil reciprocating engines. No ELV is available in the MCPD for this plant-fuel-emissions category. Particulate filters and primary technologies like choice of fuel (cleaner fuels) are employed by these plants to reduce SO_2 emissions. Like the NO_x data for this plant-fuel-pollutant category, the root cause analysis (Steps 4 and 5) conclusions are similarly inconclusive. Again, a mild trend with plant size is shown, based in few data points.

Figure 3-13 SO_2 emissions from gas oil engines

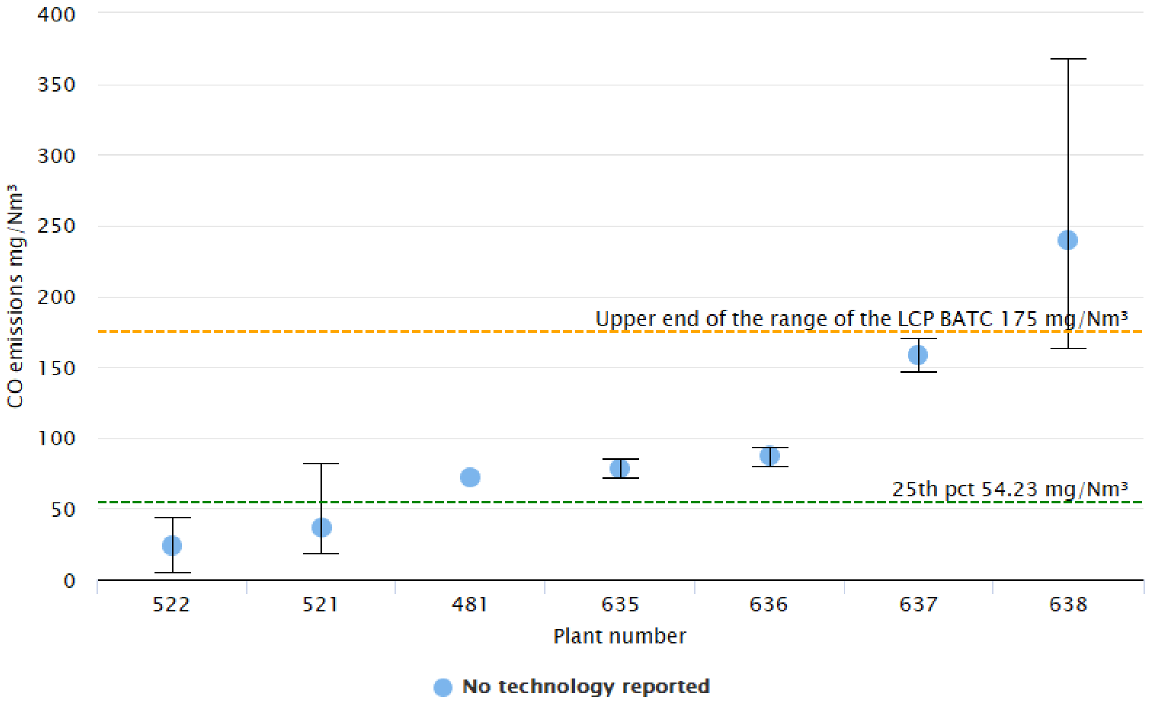


The plant reported to be burning fuel with a low sulphur content (#521 and #522) deliver the lowest SO_2 emissions level.

3.1.6.4 CO emissions from gas oil engines

As shown in Figure 3-14, for CO there are no ELVs in the MCPD, so the upper end of the range of the indicative values from the LCP BAT conclusions is displayed instead. ~ 85% perform below this value. No abatement technologies are used by the gas oil engine plants to give context to this performance.

Figure 3-14 CO emissions from gas oil engines



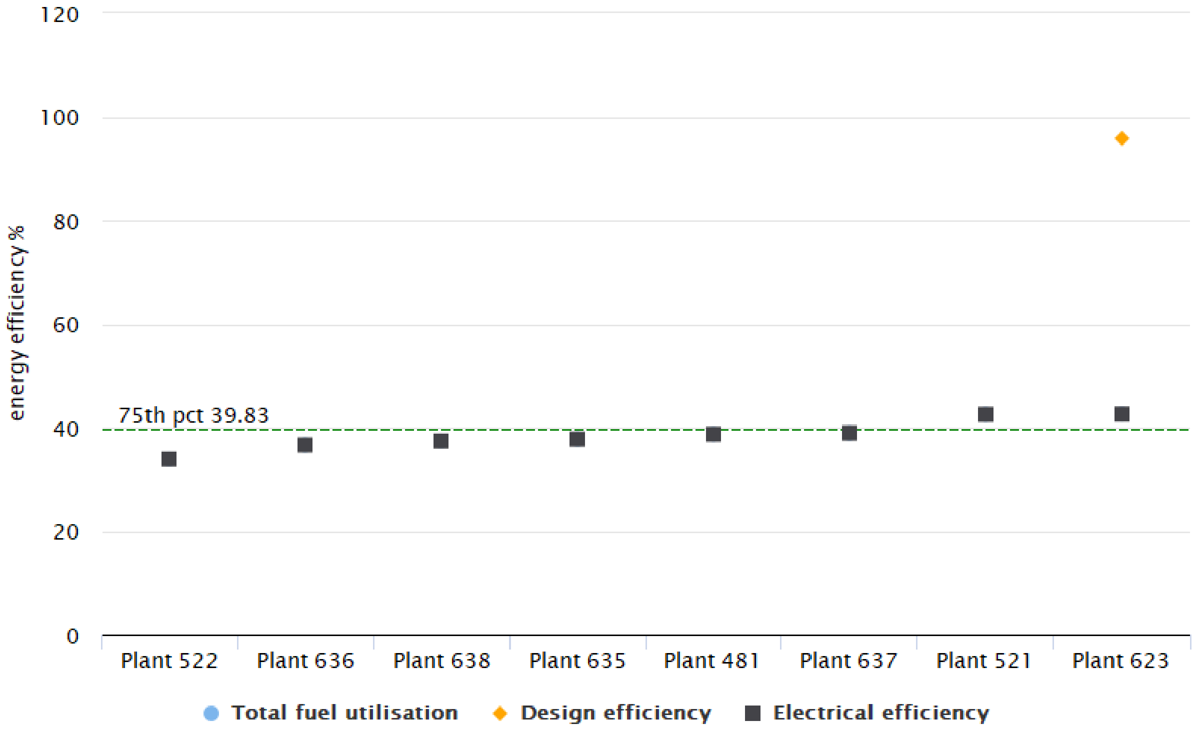
The root cause analysis did not show there to be a relationship of emissions with load factor or plant age, but it did show that plant size is a potential candidate as a root cause for the differences in CO emissions, with larger plants consistently emitting more than smaller ones. As all plants in this category are part of SIS/MIS, no comparison can be done with non-SIS/MIS plants.

Plants #521 and #522 have lower CO (and NOx, SOx and dust) emissions than the rest. These are not the most modern engines (2007), running at medium loads (60-70%) using DPF as abatement for dust.

3.1.6.5 Energy efficiency of gas oil engines

Figure 3-15 shows the energy efficiency of gas oil engines. The 75th percentile value lies at 39.8% total fuel utilisation. The variation is small, and no plants are displaying low performance. No conclusive evidence on any relationship between load factor, size and age could be found.

Figure 3-15 Energy efficiency of gas oil engines



3.1.7 Performance of plants using other liquid fuels

3.1.7.1 NO_x emissions from other liquid fuel engines

Figure 3-16 shows the NO_x emissions of other liquid fuel reciprocating engines. There is an important ELV exception for this category at 1850 mg/Nm^3, which applies to existing plants whose construction started before 18 May 2006[9]. This ELV is significantly higher than the ELV value for new and existing plants at 190 mg/Nm^3. Only 2 out of 8 (25%) of plants would meet their appropriate SIS/MIS limit value, with 4 plants showing emissions above 1850 mg/Nm^3, and 2 high speed engines showing emissions above their designated ELV of 750 mg/Nm^3. Details on which plants in the figure belong to which ELV can be found in Appendix 1. No abatement technologies are employed by these plants to reduce NO_x emissions. Best performers, MCPs #530 and #531, are high speed engines burning biomass derived liquid fuels whilst the rest are medium or low speed burning HFO. Best performers in NOx emissions do not have high CO emissions (see section 3.1.7.4). No specific abatement technologies were reported, even though Primary technologies could ensure these plants meet their current MCPD ELVs for existing plants(See section 3.2.5.1 on data from literature).

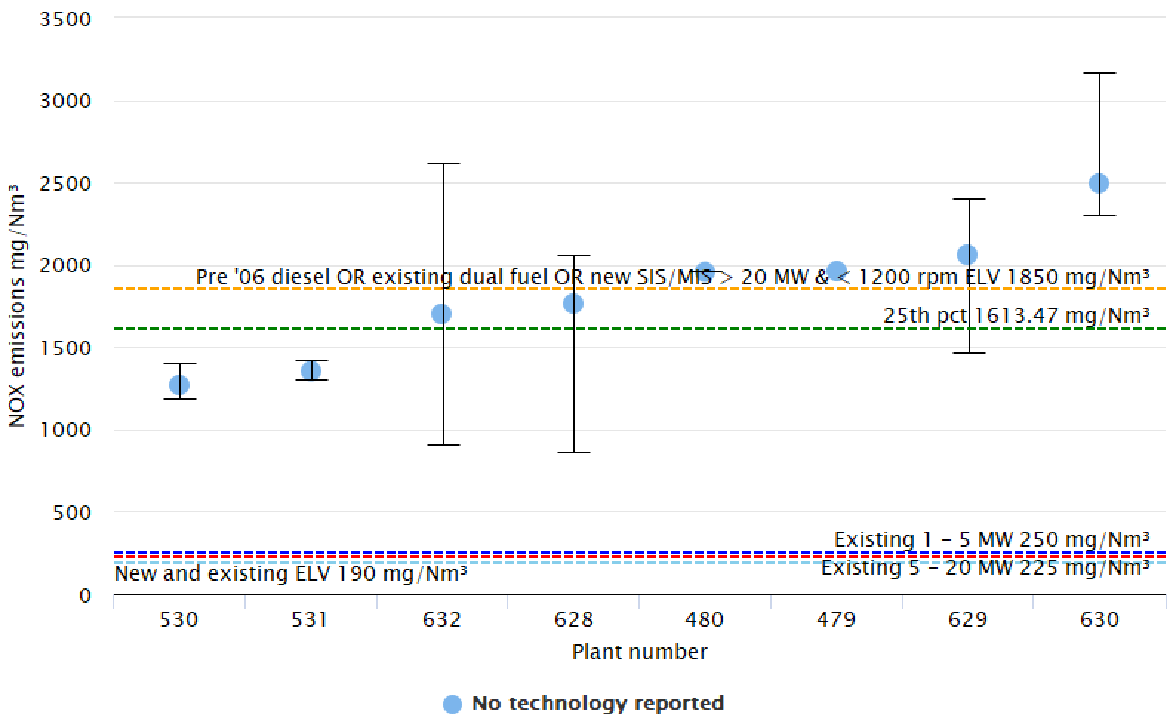
The root cause analysis did not show there to be a relationship of emissions with load factor or plant age, but it did show that plant size is a potential candidate as a root cause for the differences in emissions, with larger plants consistently outperforming smaller ones. As all plants in this category are part of SIS/MIS, no comparison can be done with non-SIS/MIS plants. The limit value for non-SIS/MIS plants is much lower at 190 mg/Nm^3, and no plant among the 8 in the survey data are close

---

[9] MCPD Annex II, part I, footnote 3: 1850 mg/Nm3 in the following cases: (i) for diesel engines the construction of which commenced before 18 May 2006; (ii) for dual fuel engines in liquid mode

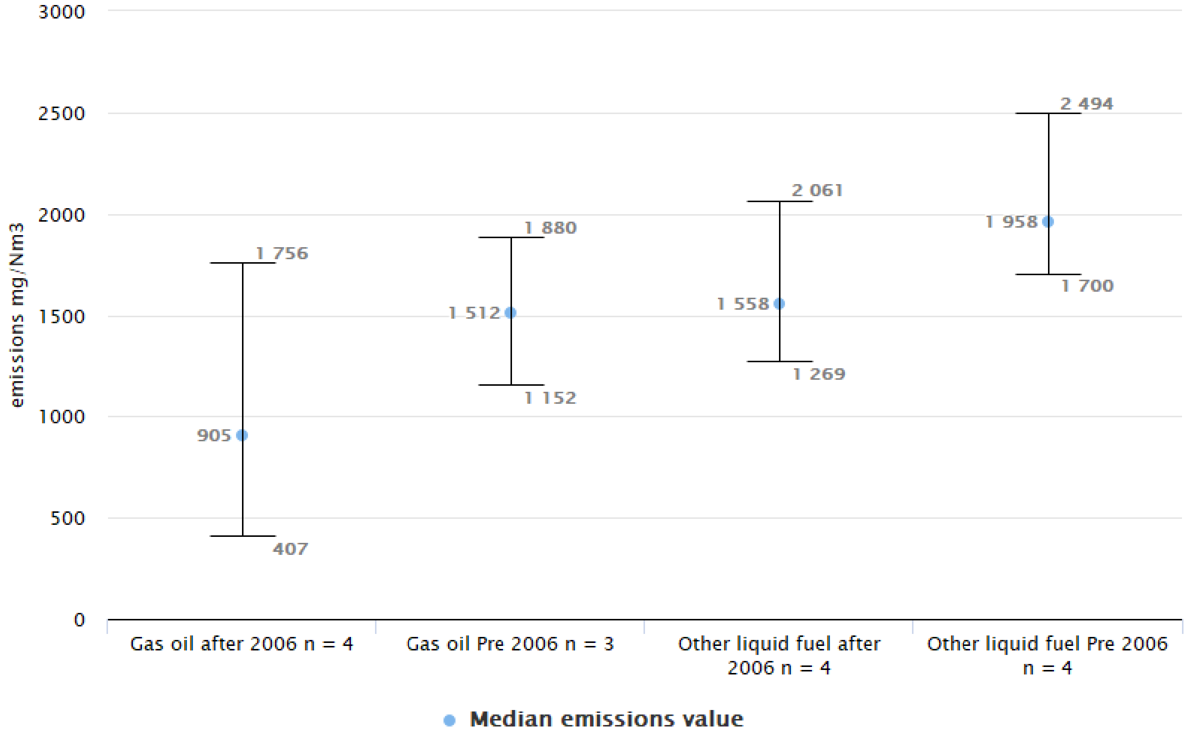
to it, with a lowest average emissions value in 1269 mg/Nm³. Nitrogen content of fuel does not have a clear impact on emissions based on the reported data.

Figure 3-16 NO$_x$ emissions from other liquid fuel engines



It should be noted that the ELV for existing plants whose construction was started before May 2006 in this category is equal to the SIS/MIS ELV, and nearly 10 times as high as the default ELV. The data from the survey has been analysed to understand if this split can also be seen in our sample. The results are visible in Figure 3-17, showing the range of emissions values across gas oil and other liquid fuel plants before and after 2006. An important caveat is that all plants in our sample which have meaningful data are part of SIS/MIS, and these are still allowed to adhere to the 1850 mg/Nm³ ELV under certain conditions. Therefore, Figure 3-17 should be interpreted with this limitation. Data is shown for both this category and Gas Oil in section 3.1.6.

Figure 3-17 Comparison of NOx emissions pre and post 2006 for gas oil and other liquid fuel engines

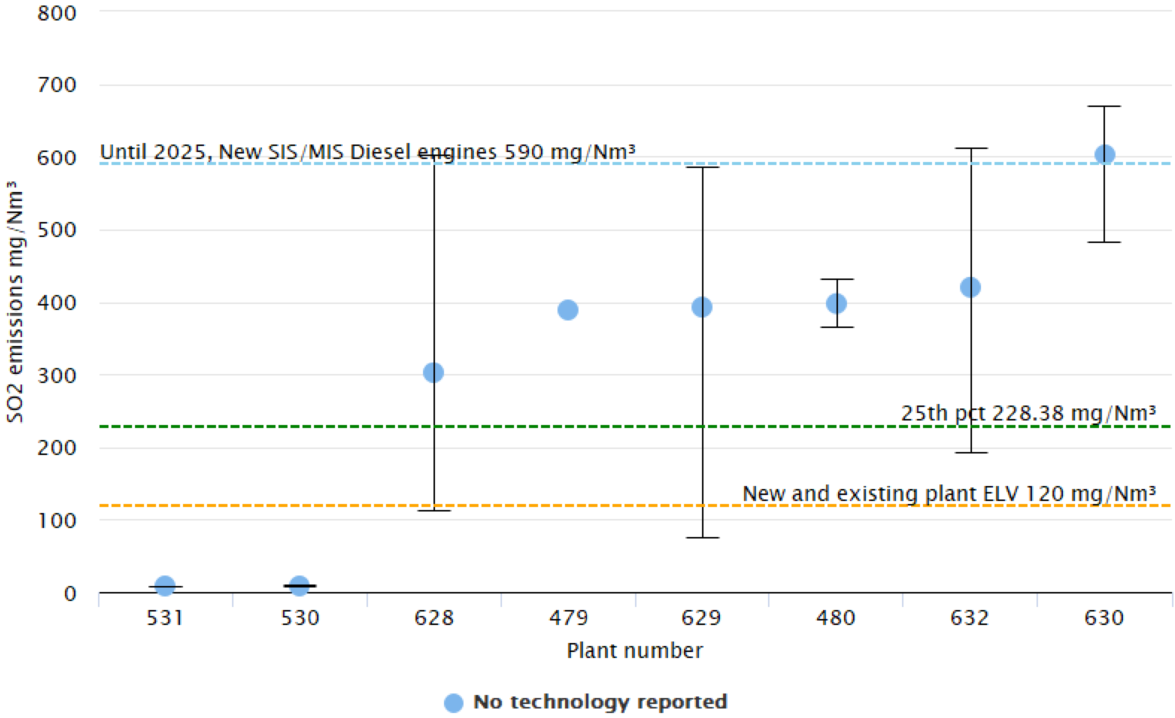


From Figure 3-17 the data reported does not indicate that older plants are significantly more polluting than newer plants for ‘other liquid fuel’, but the median difference is significant for ‘gas oil’.

3.1.7.2 SO_2 emissions from other liquid fuel engines

Figure 3-18 shows the SO_2 emissions of other liquid fuel reciprocating engines. Most (7 out of 8) plants meet the limit value for new SIS/MIS plants until 2025. No abatement technologies are employed by these plants to reduce SO_2 emissions. Best performers, MCPs #530 and #531 that meet the limit value for new and existing plants of 120 mg/m^3, are high speed engines burning biomass derived liquid fuels whereas the rest are medium or low speed burning HFO.

Figure 3-18 SO_2 emissions from other liquid fuel engines



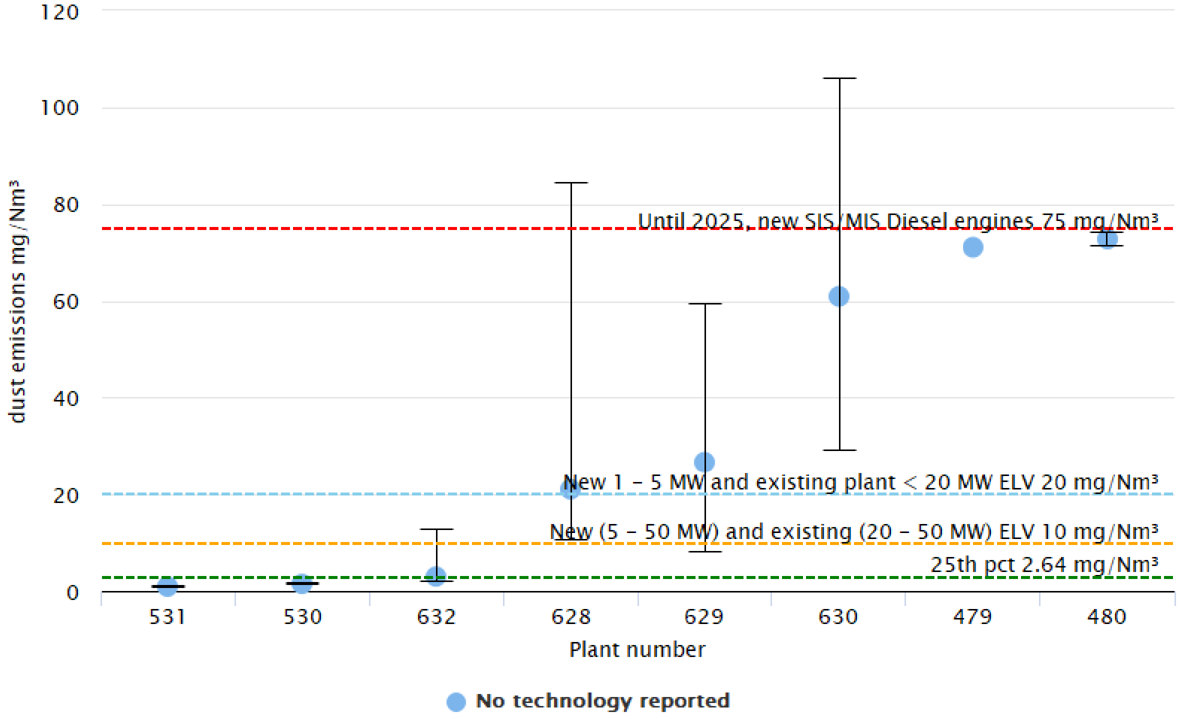
The root cause analysis did not show there to be a relationship of emissions with load factor or plant size, but it did show that plant age is a potential candidate as a root cause for the differences in emissions, with newer plants consistently emitting less than older plants. As all plants in this category are part of SIS/MIS, no comparison can be done with non-SIS/MIS plants.

Regarding plants burning HFO, there is a clear correlation with sulphur content in fuel leading to higher SO_2 emissions: see Appendix 1 for further details. Correlations may be altered because some emissions data may have been averaged when operating with various fuels qualities (different sulphur contents).

3.1.7.3 Dust emissions from other liquid fuel engines

Figure 3-19 shows the dust emissions of other liquid fuel reciprocating engines. 37% (3 out of 8) of plants meet the ELV for new plants. When comparing to the ELV for existing plants, one more plant is compliant. No abatement technologies are employed by these plants to reduce dust emissions. Best performers, MCPs #530 and #531, are high speed engines burning biomass derived liquid fuels whereas the rest are medium or low speed burning HFO. The share of gasoil use (low in most cases) may have an impact on dust emission values reported.

Figure 3-19 Dust emissions from other liquid fuel engines

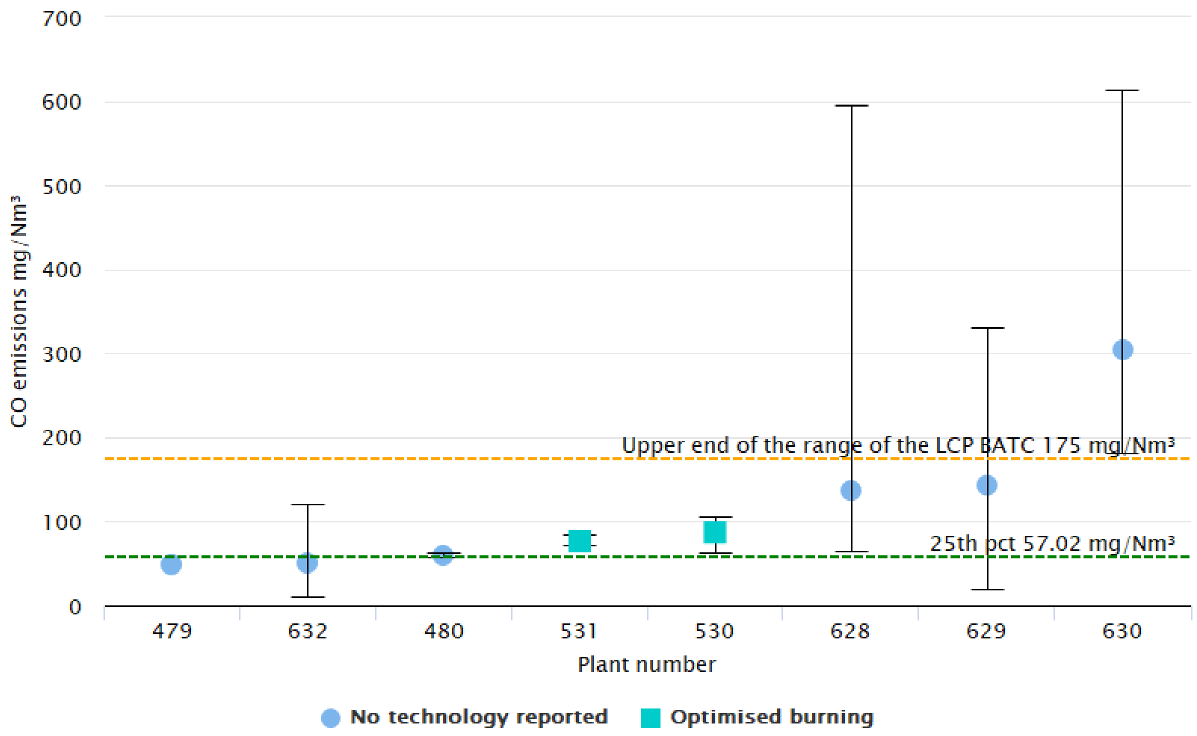


The root cause analysis (Steps 4 and 5) conclusions are inconclusive. High correlation coefficients are found with plant age, size and rate, but none of these are from uniform distributions among the 8 data points. Therefore, no linear relationships are observed and no variables can be concluded as being a root cause for the emissions of dust from this plant-fuel-emissions category.

3.1.7.4 CO emissions from other liquid fuel engines

As shown in Figure 3-20, for CO there are no ELVs in the MCPD, so the upper end of the range of the indicative values from the LCP BAT conclusions is displayed instead. ~ 88% (7 out of 8) perform below this value to a reference value in this instance. Optimised combustion is used by two MCPs in this cluster (#531 and #530). Best performers emitting the lowest CO levels are not generating the highest NOx emissions (see section 3.1.7.1).

Figure 3-20 CO emissions from other liquid fuel engines

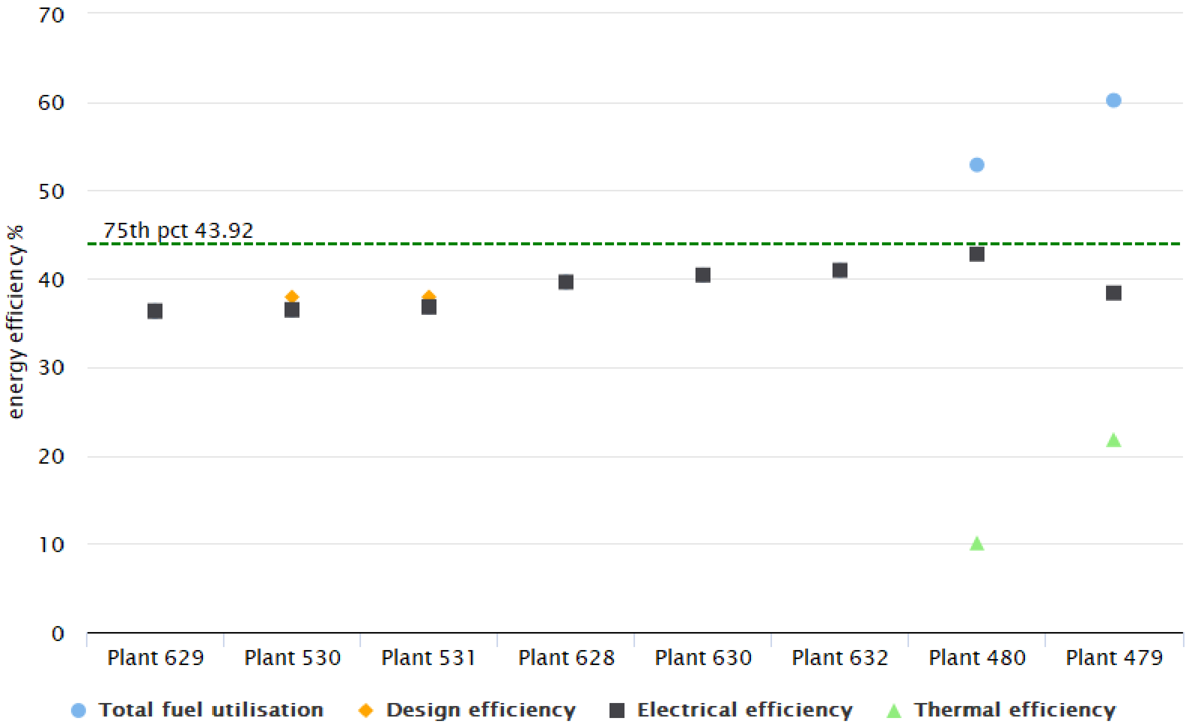


Similar to other pollutants, the root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of plant age, rate or size, due to small sample size (load factor) or non-homogeneous distributions (plant size, plant age).

3.1.7.5 Energy efficiency of other liquid fuels engines

Figure 3-21 shows the energy efficiency of this cluster. The 75th percentile value lies at 43% total fuel utilisation. The variation is small, and no plants are displaying low performance (regardless of being different engine types and different fuels). No conclusive evidence on any relationship between plant size and age could be found. Higher plant loads are delivering higher energy efficiencies (see Appendix 1 of this document).

Figure 3-21 Energy efficiency of other liquid fuels engines

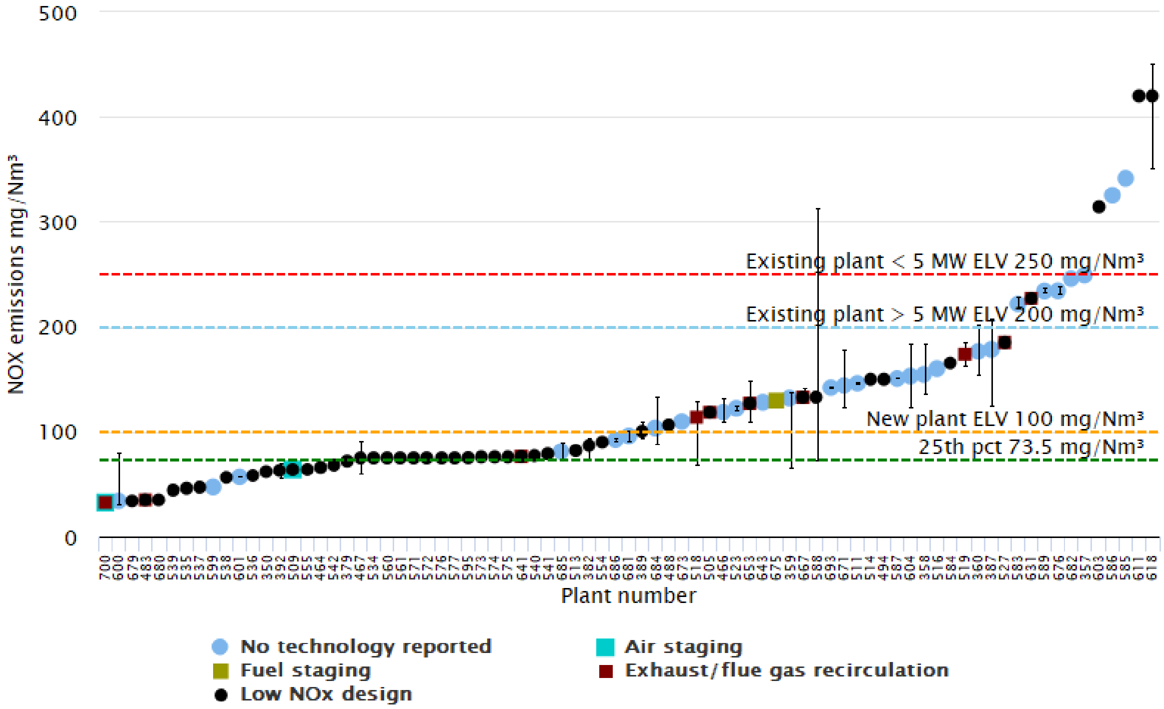


3.1.8 Performance of plants using natural gas

3.1.8.1 NO_x emissions from natural gas boilers

Figure 3-22 shows the NO_x emissions from natural gas boilers. Just over half (54%) of these MCPs meet the limit value for new plants, and ~ 84% of them meet the ELV for existing plants. Four abatement technologies are employed for NO_x reduction. Of these, air staging, low NO_x design and exhaust/flue gas recirculation are technologies applied by the 25% best performing plants at less than 73 mg/Nm^3. None of the plants emitting below 25th percentile (73 mg/Nm^3) are emitting high CO values.

Figure 3-22 NO_x emissions from natural gas boilers



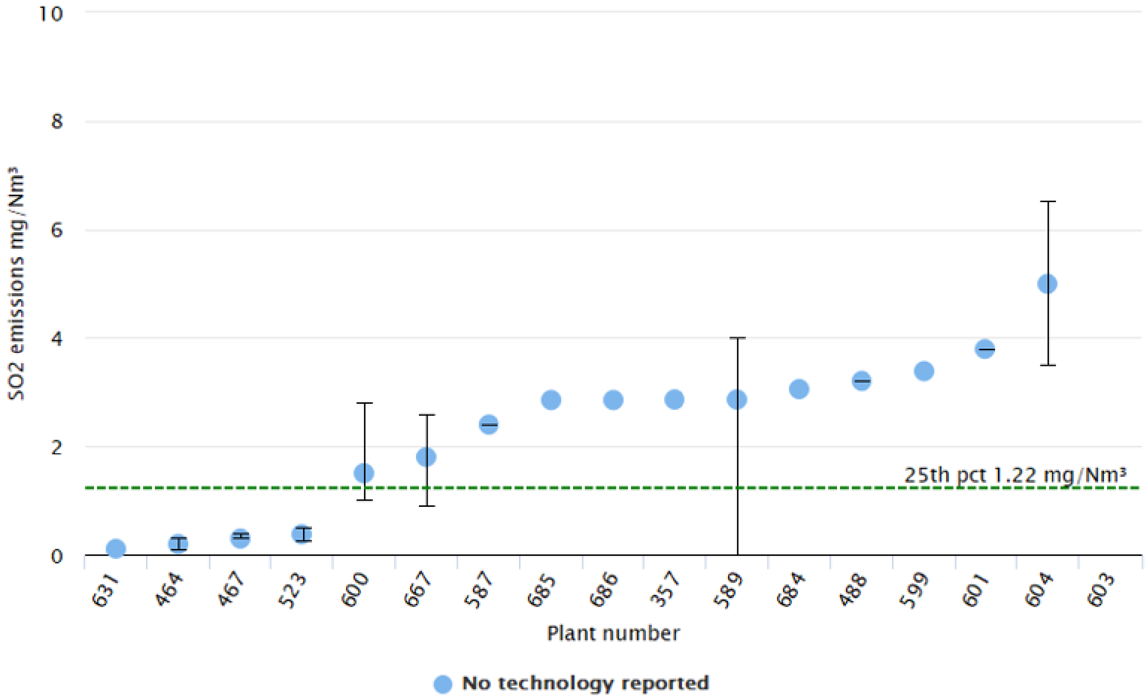
Note that some plant may use multiple technologies, therefore the points can overlap and not all technologies are visible on the chart. See the interactive chart in Appendix 1 to isolate the effect of individual technologies.

The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with load factor nor size. Plant age is a potential candidate as a root cause for the differences in emissions, with newer plants (commissioned after 2012) consistently outperforming older plants. The data reported does not show that Nitrogen content in fuel does would deliver an impact on emissions.

3.1.8.2 SO_2 emissions from natural gas boilers

As shown in Figure 3-23, there is no limit value for this plant-fuel-emissions category in the MCPD. SO_2, like dust, is not a pollutant of significant concern for this category. Unsurprisingly therefore, no abatement technologies are applied by the sample of plants. As the low SO_2 emissions are expected to be caused by low sulphur contents in the fuel, no root cause analysis is undertaken for this category.

Figure 3-23 SO_2 emissions from natural gas boilers (lower range 0 – 10 mg/Nm^3 excluding outlier 603) *

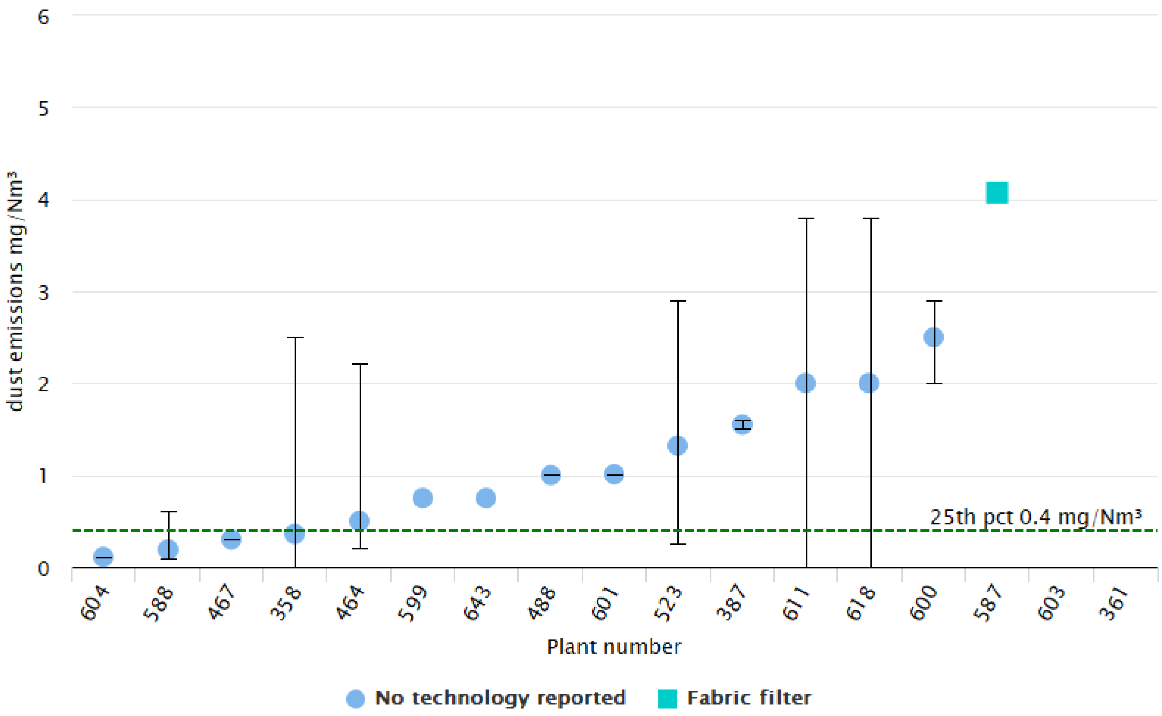


**Note: the data for plant 603 contains an outlier at 117 mg/Nm^3. The above figure has been zoomed in to the 0 – 10 mg/Nm^3 range to display the expected low range of SO_2 emissions for this category. The outlier has been discarded for analysis and a clarification was sought from the Member State but not received in time for inclusion in this report. In Appendix 1, you can draw a box on the lower part of the graph to zoom to the level as displayed in Figure 3-23.*

3.1.8.3 Dust emissions from natural gas boilers

As shown in Figure 3-24, there is no limit value for this plant-fuel-emissions category in the MCPD. Similar to SO_2, dust is not a pollutant of significant concern for this category. As the overall low dust emissions are expected to be caused by low dust contents in the fuel and combustion conditions, no root cause analysis is undertaken for this category.

Figure 3-24 Dust emissions from natural gas boilers (lower range 0 – 6 mg/Nm^3 excluding outliers 603 and 361) *



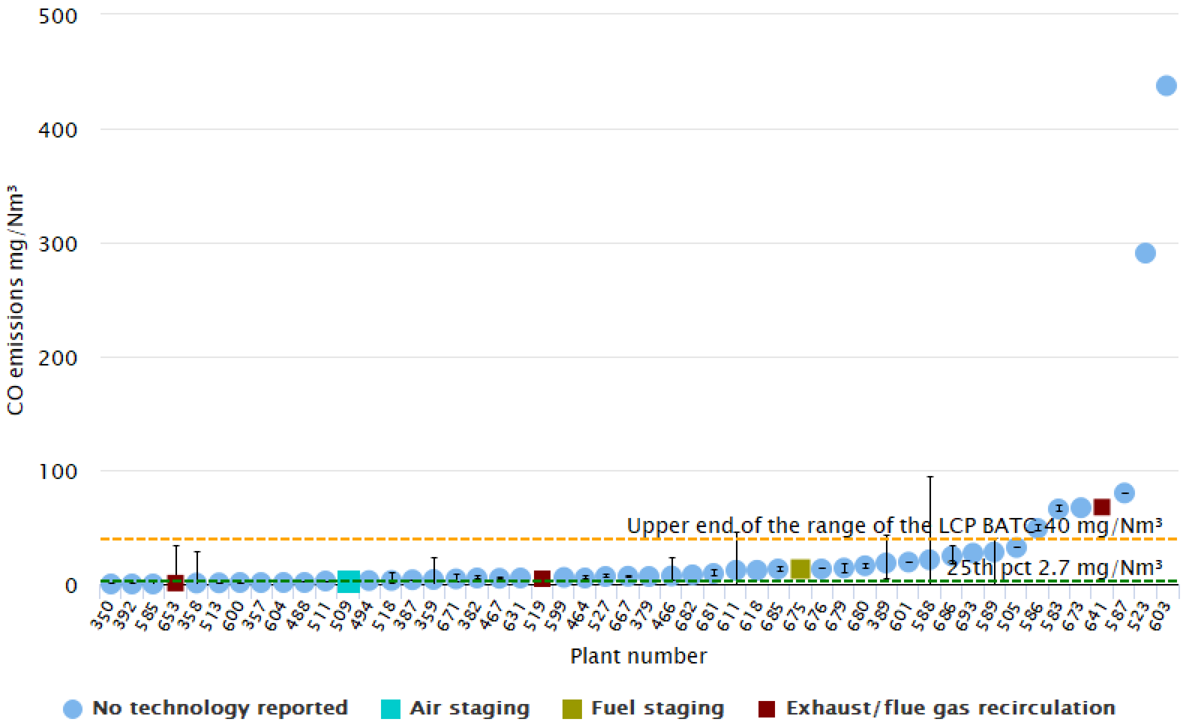
** Note: the data for plants 603 and 361 are unexpected outliers at 66 and 91 mg/Nm^3 respectively. The above figure has been zoomed in to the 0 – 6 mg/Nm^3 range to display the expected low range of dust emissions for this category. The outliers have been discarded for analysis and a clarification was sought from the Member State but was not received in time for inclusion in this report. In Appendix 1, you can draw a box on the lower part of the graph to zoom to the level as displayed in Figure 3-24.*

3.1.8.4 CO emissions from natural gas boilers

Figure 3-25 shows the CO emissions from natural gas boilers. For CO there are no ELVs in the MCPD, so the upper end of the range of the indicative values from the LCP BAT conclusions is displayed instead, using the value from existing plants (range 5 – 40 mg/Nm³). Approximately 89% perform below this value. The 25% best performing plants employ air staging or flue gas recirculation. MCPs generating the lowest emission levels do not have the highest NOx levels (see section 3.1.8.1).

The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with plant age, rate or size. Two new plants are among the best performers.

Figure 3-25 CO emissions from natural gas boilers

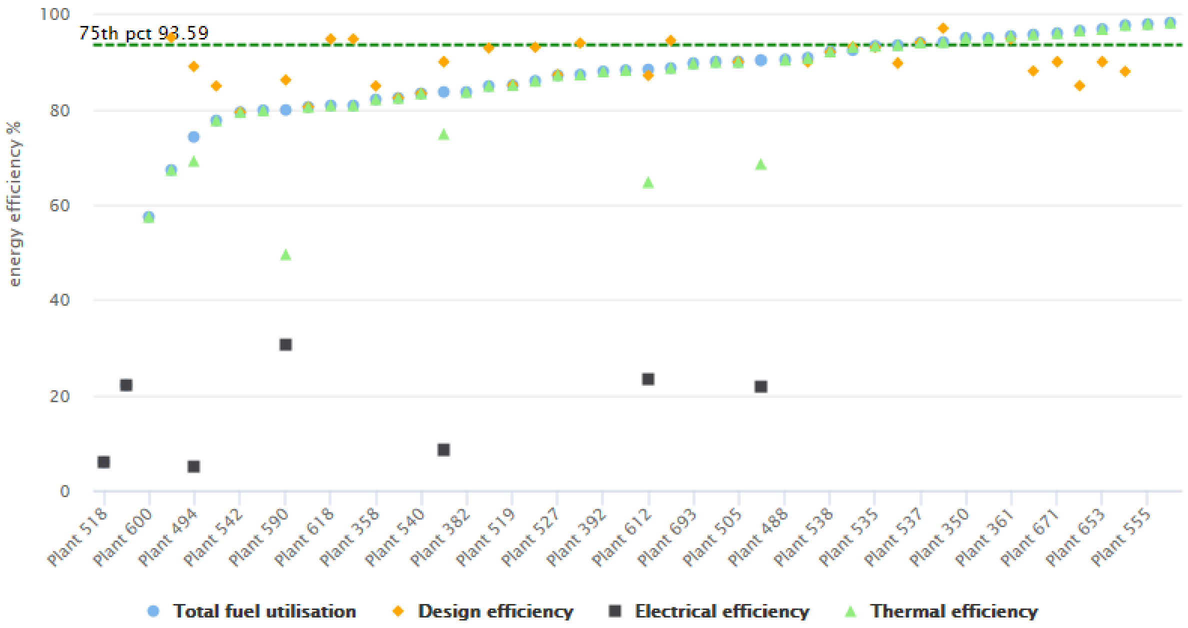


3.1.8.5 Energy efficiency of natural gas boilers

Figure 3-26 shows the energy efficiency of natural gas boilers. The 75th percentile value lies at 93% total fuel utilisation. Several plants at the low end of the efficiency scale report design efficiencies that are around the average, suggesting they are underperforming. CHP MCPs have an electrical efficiency ranging from 5 to 30% but total fuel utilisation is not significantly different to the rest of the boilers.

From a root cause perspective, there is a weak correlation of load factor total fuel utilisation (might be due to having many data points at 100% rate). Due to a heterogeneous distribution, this cannot be directly interpreted as evidence of a relationship, but it can be seen in Appendix 2 that plants with a higher load factor have more variation in their energy efficiency.

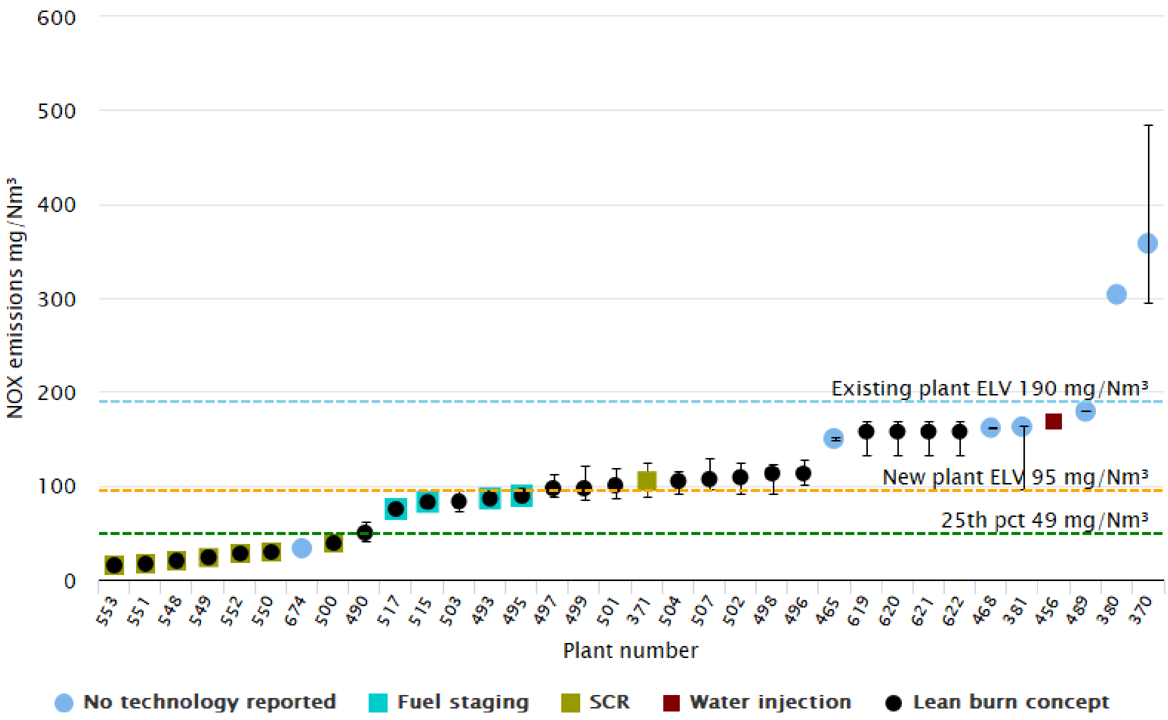
Figure 3-26 Energy efficiency of natural gas boilers



3.1.8.6 NO$_x$ emissions from natural gas engines

Figure 3-27 shows the NO$_x$ emissions from natural gas engines. Only one data point (#456) is coming from a high speed (>1200rpms) engine. 42% of these MCPs meets the limit value for new plants, and ~ 94% of them meet the ELV for existing plants. Four technologies are employed for NO$_x$ reduction. Of these, SCR and 'Lean-burn concept' are used by best performers (25th percentile). MCPs delivering the lowest NOx emissions in the sample are not generating the largest CO emissions.

Figure 3-27 NO$_x$ emissions from natural gas engines

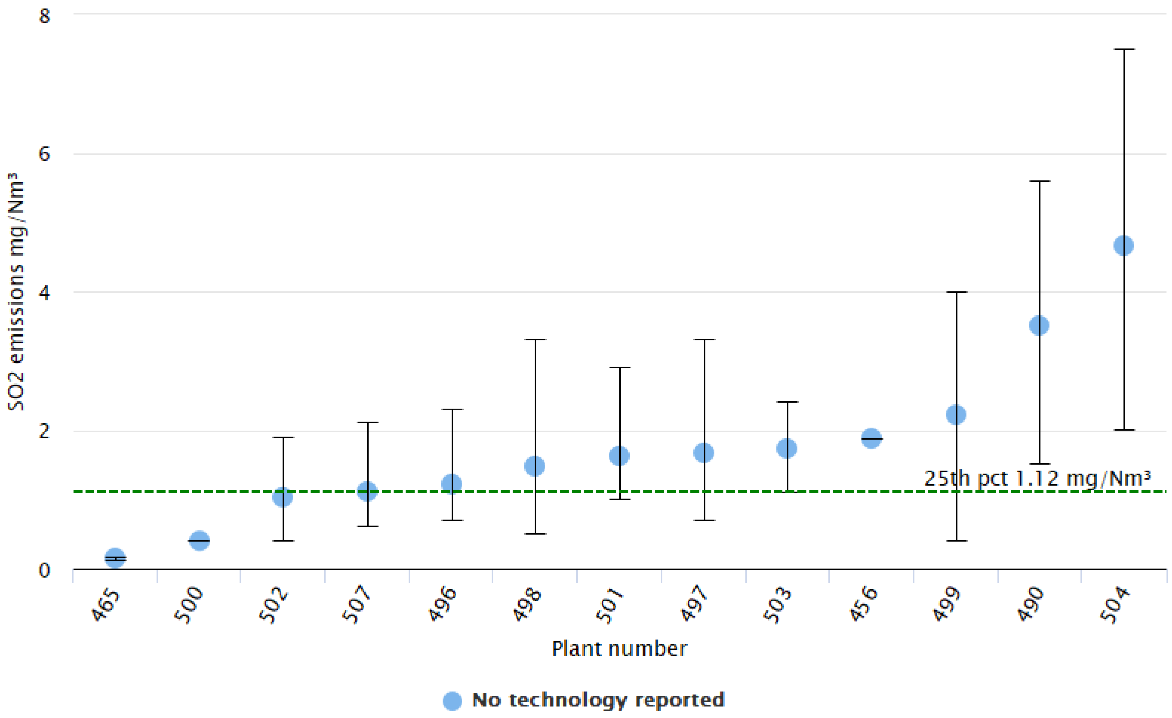


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with load factor, size or age. For this sample set, nitrogen content of fuel is not a clear factor on NOx emissions. Great share of this emission data (around 40%) was provided by MCP plants operating at lower loads, lower than 70% of their design capacity.

3.1.8.7 SO_2 emissions from natural gas engines

As shown in Figure 3-28, there is no limit value for this plant-fuel-emissions category in the MCPD. Similar to the approach for natural gas boilers in section 3.1.8.2, SO_2 and dust are not pollutants of significant concern for this category. Unsurprisingly therefore, no abatement technologies are applied by the sample of plants. As the low SO_2 emissions are expected to be caused by low sulphur content in the fuel, no root cause analysis is undertaken for this category.

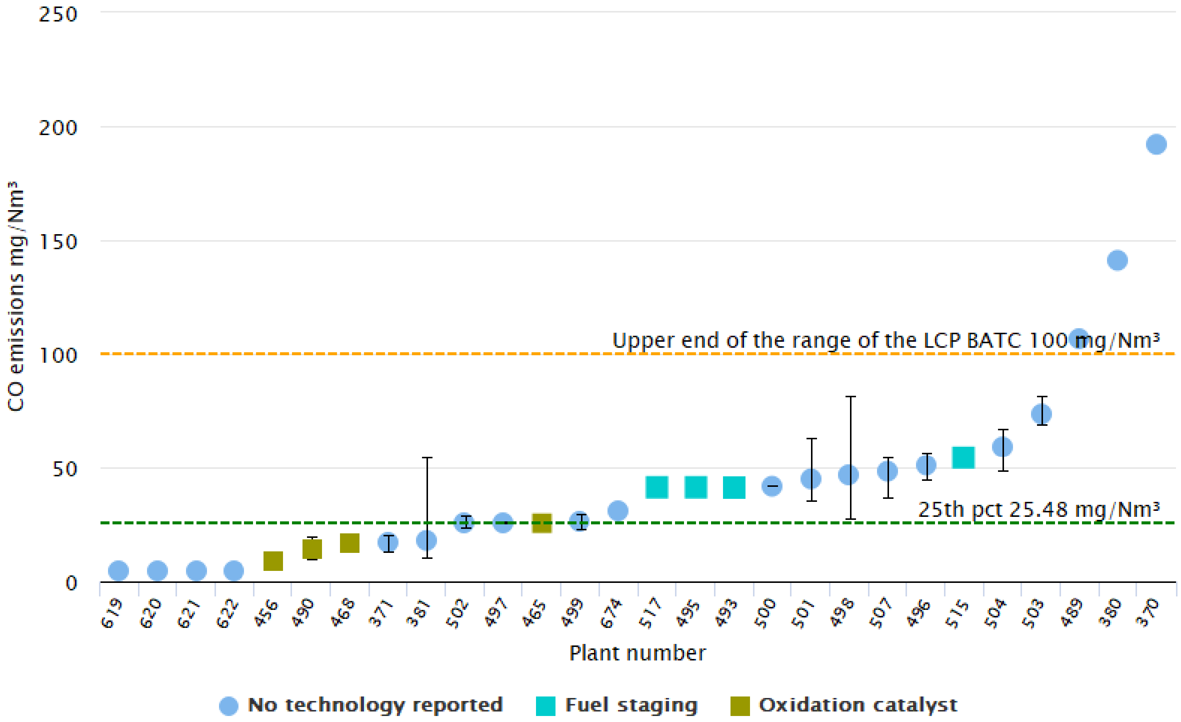
Figure 3-28 SO_2 emissions from natural gas engines



3.1.8.8 CO emissions from natural gas engines

Figure 3-29 shows the CO emissions from natural gas engines. For CO there are no ELVs in the MCPD, so the upper end of the indicative values from the LCP BREF is displayed instead. ~ 95% performs below this value. Oxidation catalyst (used by best performers) and fuel staging are applied by MCPs in this sample to reduce CO emissions. There are both low and high speed (>1200 rpms) engines among the best performers. Plants delivering the highest CO emissions are not the best performers for NOx emission levels.

Figure 3-29 CO emissions from natural gas engines



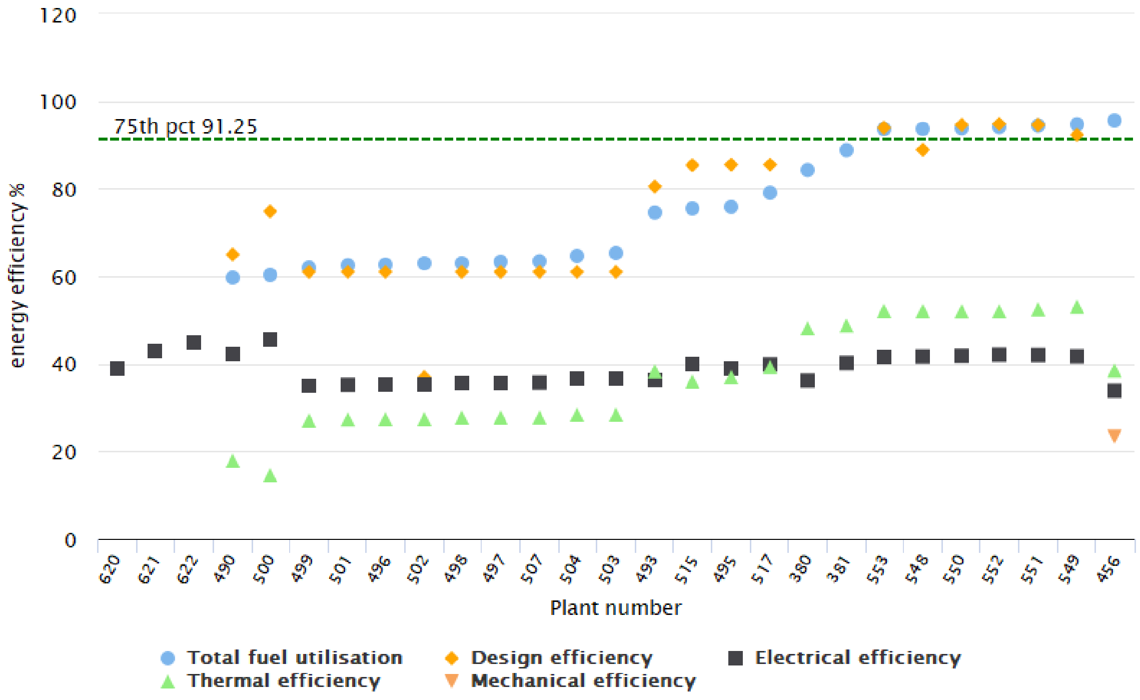
Note: plants #619-622 may have achieved these low CO values with oxidation catalyst but this was not validated. These plants have not been used to calculate the 25th percentile range.

The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with plant age or size. Load factor showed a correlation visible with CO emissions, with the highest emissions produced also having the highest load factor. MCPs commissioned after 2013 are all emitting below the indicative reference value (less than rest).

3.1.8.9 Energy efficiency of natural gas engines

Figure 3-30 shows the energy efficiency of natural gas engines. Plant #619 is an outlier. The 75th percentile value lies at 90% total fuel utilisation. Most MCPs in this sample are CHPs with electrical efficiencies ranging between 35-42% and thermal efficiencies ranging between 36-50%. There is one MCP for mechanical drive purposes with high total fuel utilisation.

Figure 3-30 Energy efficiency of natural gas engines

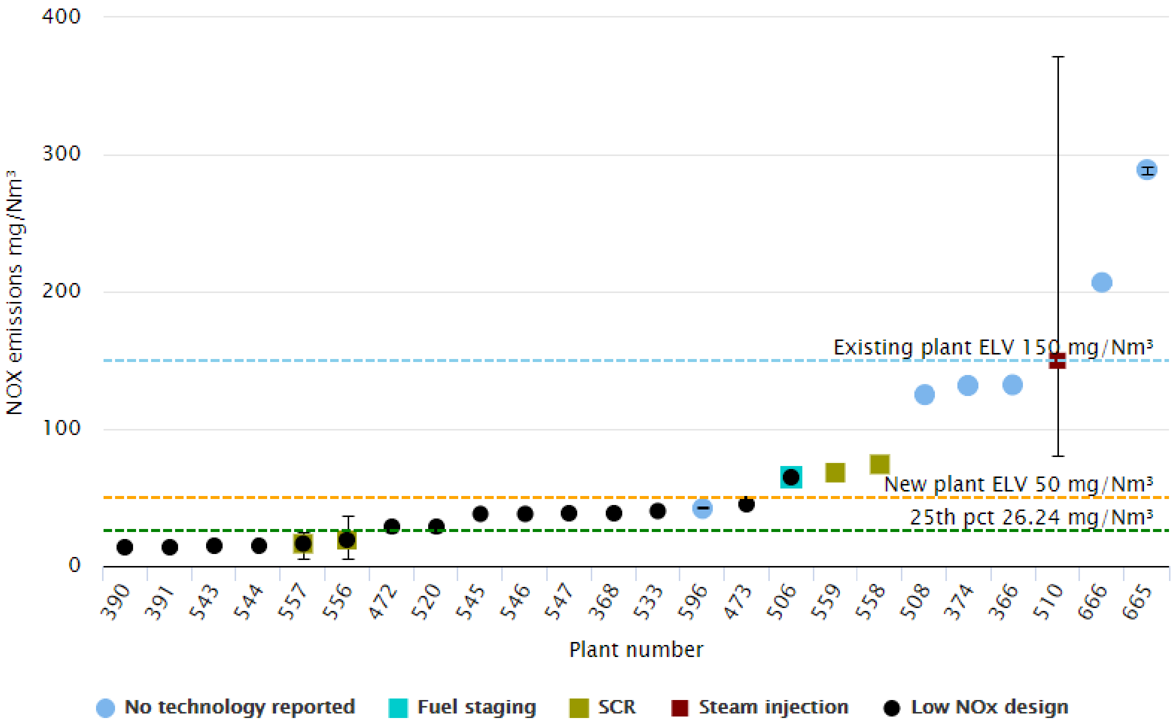


From a root cause perspective, oldest plants in the sample do consistently outperform even the newest plants. This further points to the notion that total fuel utilisation may be subservient to other demands such as energy-consuming technologies with plants recently commissioned. Several plants (7 out of 28) reported efficiencies at loads below 70%: plant operating at higher loads are reporting higher efficiencies.

3.1.8.10 NO_x emissions from natural gas turbines

Figure 3-31 shows the NO_x emissions from natural gas turbines. Around 66% of these MCPs meet the limit value for new plants, and approximately 90% meet the ELV for existing plants. Four technologies are employed for NO_x reduction. Of these, SCR and low NO_x design is reported in the best performers. There are two MCPs (#558 and #559) that operate in offshore plant (outside of the MCPD scope) but help to demonstrate that SCR is applicable and viable in MCP turbines (and under difficult conditions).. MCPs delivering the best NOx levels are not generating the highest CO levels. There are only two best NOx performers (#543 and #544), out of six MCPs, with higher CO than average (380 mg/Nm^3).

Figure 3-31 NO_x emissions from natural gas turbines

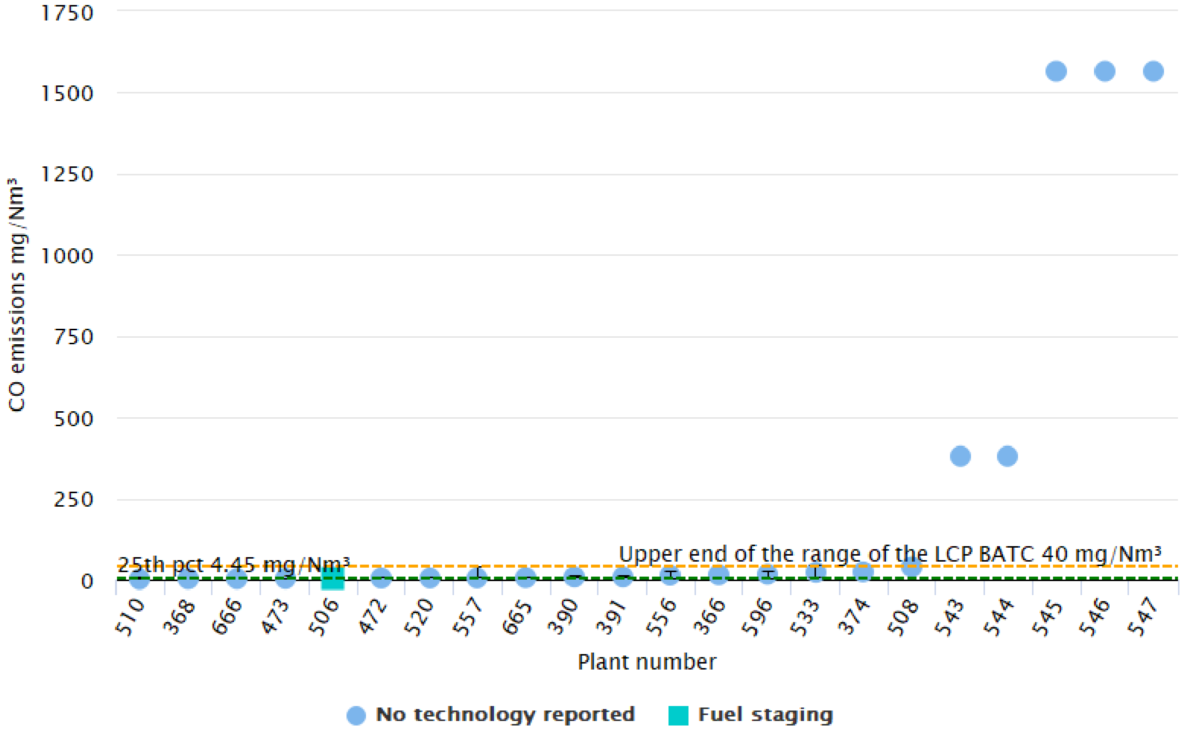


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with load factor, size or age. Nitrogen content in fuel is not a key factor impacting on emissions performance. All emissions data in this set was reported to be operating at 70% load or higher.

3.1.8.11 CO emissions from natural gas turbines

Figure 3-32 shows the CO emissions from natural gas turbines. For CO there are no ELVs in the MCPD, so the upper end of the range of the indicative values from the LCP BAT conclusions is displayed instead. Approximately 87% perform below this value. Only fuel staging is used by the sample to reduce CO (and/or NOx emissions) emissions.

Figure 3-32 CO emissions from natural gas turbines

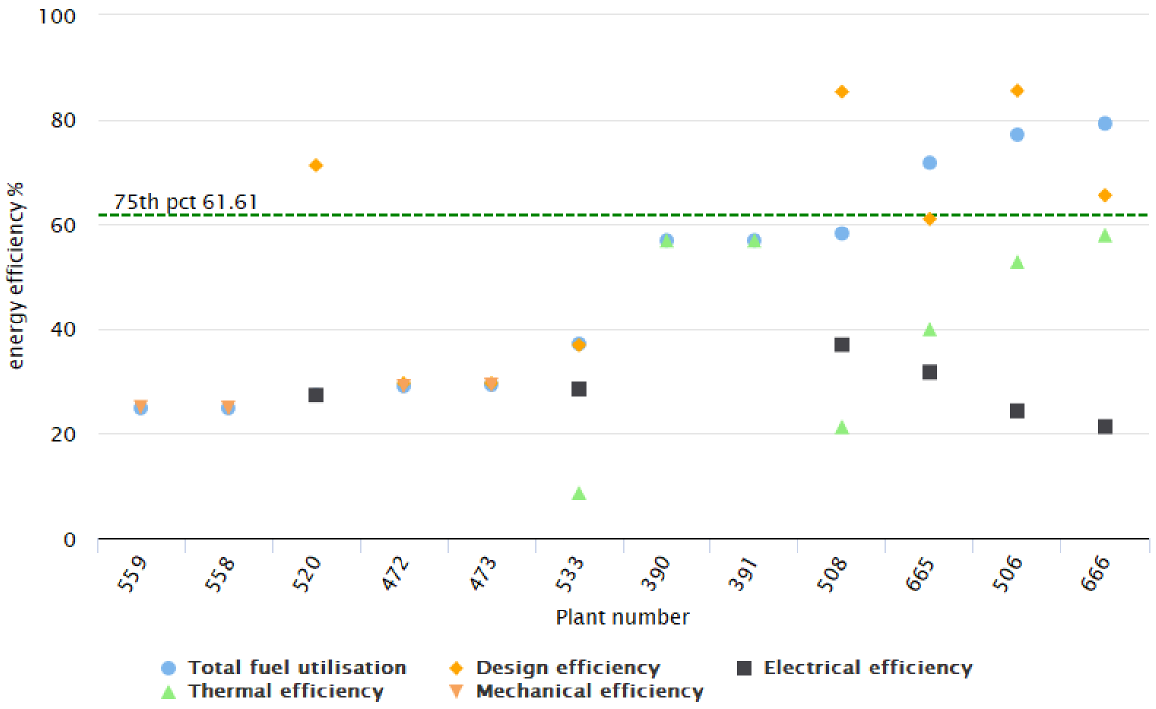


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with plant age, rate or size.

3.1.8.12 Energy efficiency of natural gas turbines

Figure 3-33 shows the energy efficiency of natural gas turbines. The best performers, 75th percentile value, lies at 61% total fuel utilisation. There is only a small sample, but it shows a large variation in reported efficiency due to different plant arrangements e.g. there are four mechanical drive plants with the lowest efficient values (e.g. plants #472 and #473). Two of these plants (#558 and #559) are in offshore plants which are out of the MCPD scope but included for the reasons discussed previously. CHP show electrical efficiencies ranging from 21-37% and thermal efficiencies in the 9-57% range.

Figure 3-33 Energy efficiency of natural gas turbines



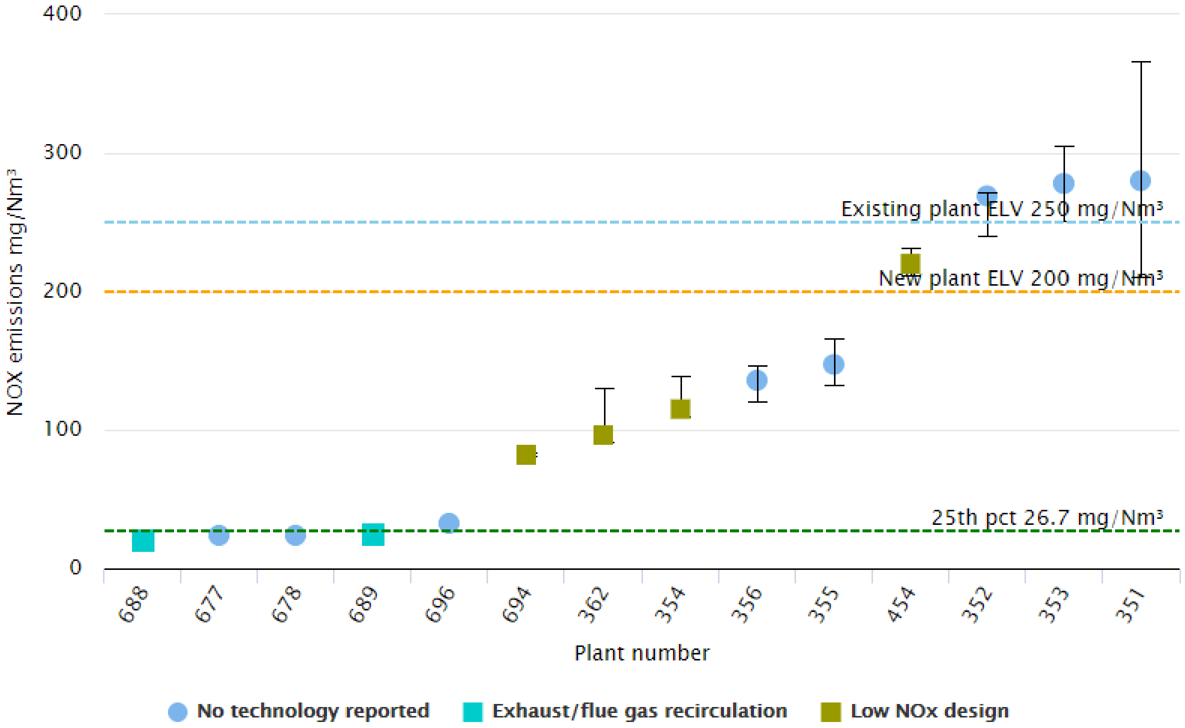
The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with plant age or size. A small correlation is seen with loads, with slightly higher efficiencies at higher loads.

3.1.9 Performance of plants using other gaseous fuels

3.1.9.1 NO_x emissions from other gaseous boilers

Figure 3-34 shows the NO_x emissions from other gaseous fuels boilers. Most MCP in this set (71%) meet the ELV in the directive for existing plants set at 250 mg/Nm^3. Exhaust/flue gas recirculation is used by the best performers. Only one best performer (#677) with the lowest NOx levels has very high CO emission levels.

Figure 3-34 NO_x emissions from other gaseous fuels boilers

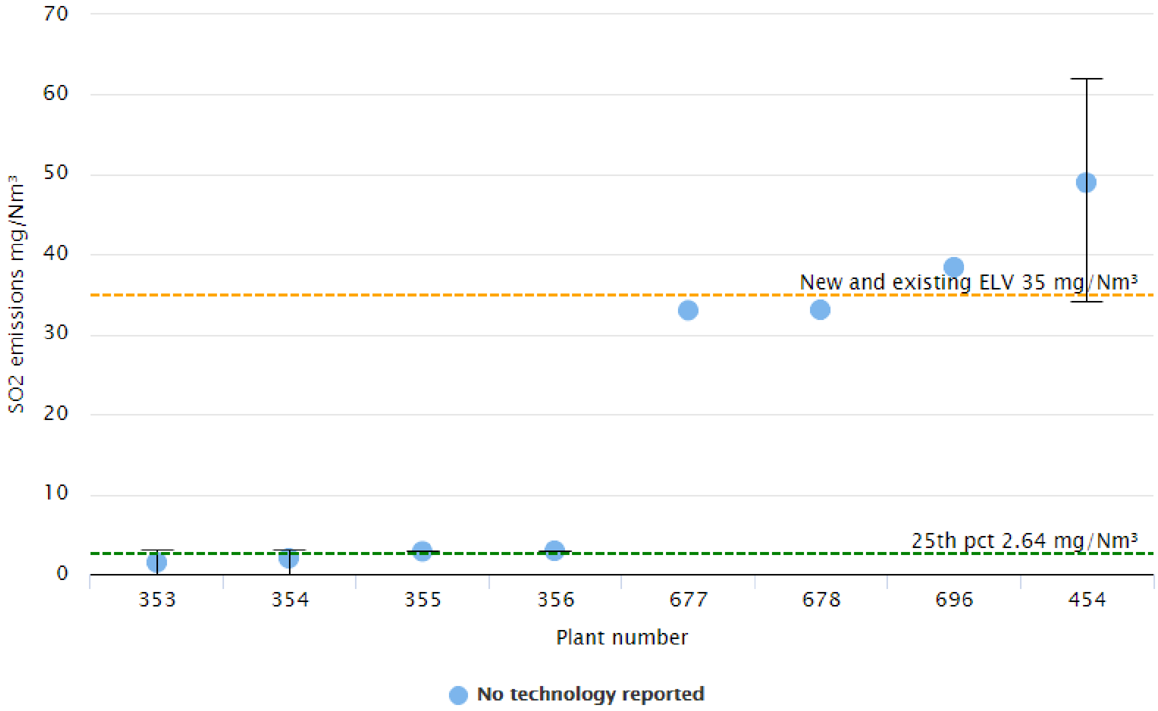


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with plant age, rate nor size. There are no SIS/MIS plants in this category. Nitrogen content in fuel does not have a clear impact on emissions. The % of natural gas in the fuel mix does not appear to have a clear impact on the emission levels (see Appendix 1 of this document).

3.1.9.2 SO_2 emissions from other gaseous fuels boilers

Figure 3-35 shows that 75% of plants directly meet the ELV from the directive. The highest value (#454) is reported by an MCP burning coke oven gas, which has an ELV of 400 mg/Nm^3. This high ELV is not shown on the figure as it would make the difference between the data points unreadable. With this plant included and referenced to the appropriate ELV, 87.5% of plants meet their MCPD ELVs.

Figure 3-35 SO_2 emissions from other gaseous fuel boilers

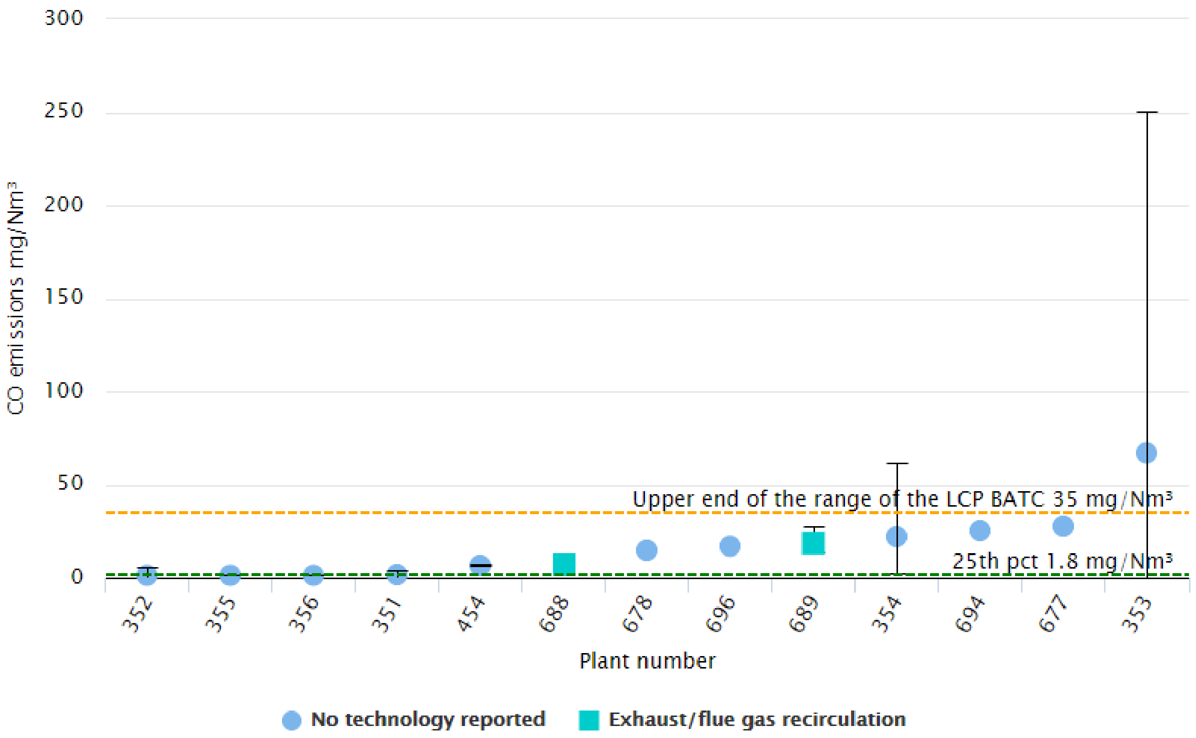


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of plant age or size. There is a great heterogeneity on the pool of fuels compositions reported by these MCPs which does not allow analysing the impact of fuel composition on SO_2 emissions (see Appendix 1 of this document).

3.1.9.3 CO emissions from other gaseous fuels boilers

Figure 3-36 shows the CO emissions from this cluster. 92% (all but one) of plants meet the indicative value from LCP BREF for 50MWth plants. Only one technology has been reported (exhaust/flue gas recirculation) but not by the best performers.

Figure 3-36 CO emissions from other gaseous fuel boilers

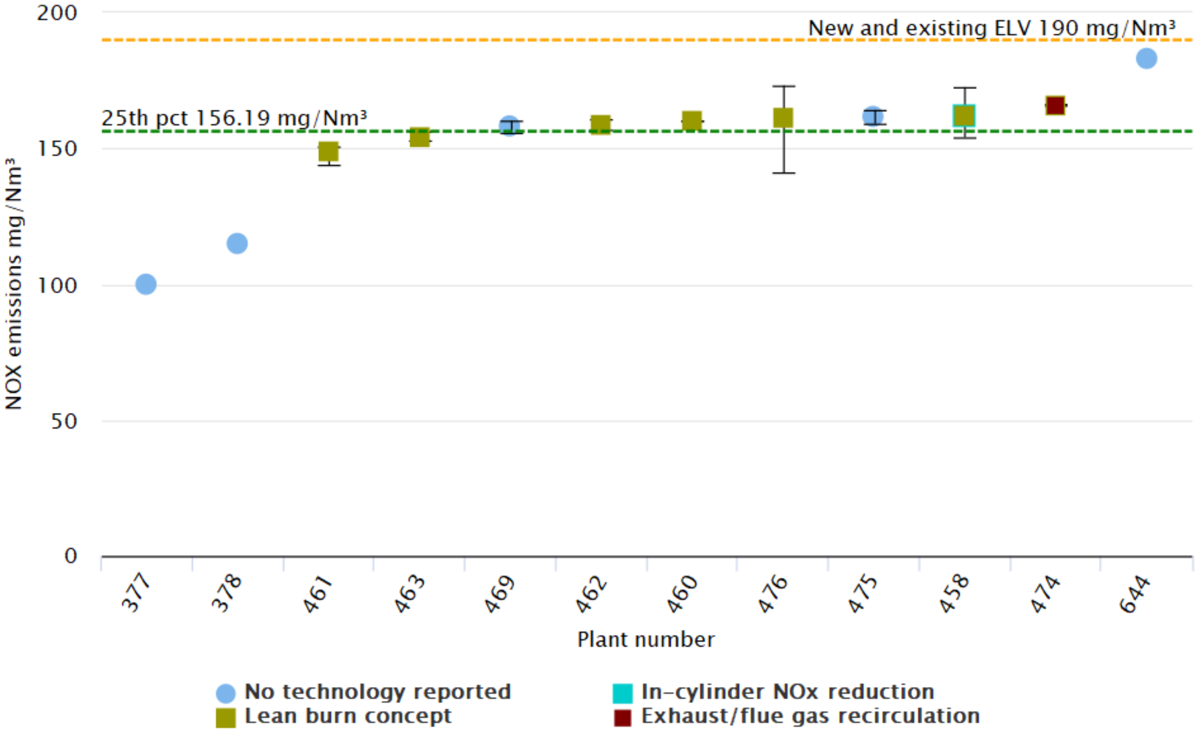


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with plant age or size. Load factor showed mild correlation visible with CO emissions, with the lowest emissions produced at a lower load factor.

3.1.9.4 NO_x emissions from other gaseous fuel engines

Figure 3-37 shows the NO_x emissions from other gaseous fuel engines. All these data were reported by high speed (>1200 rpms) engines. 100% of these MCPs meet the limit value for new and existing plants. The sample applies the lean burn concept, in-cylinder NO_x reduction and exhaust/flue gas recirculation, but only lean burn is used in the best performing plants. One of the NOx best performers (#378) delivers one of the highest CO emissions reported.

Figure 3-37 NO_x emissions from other gaseous fuel engines



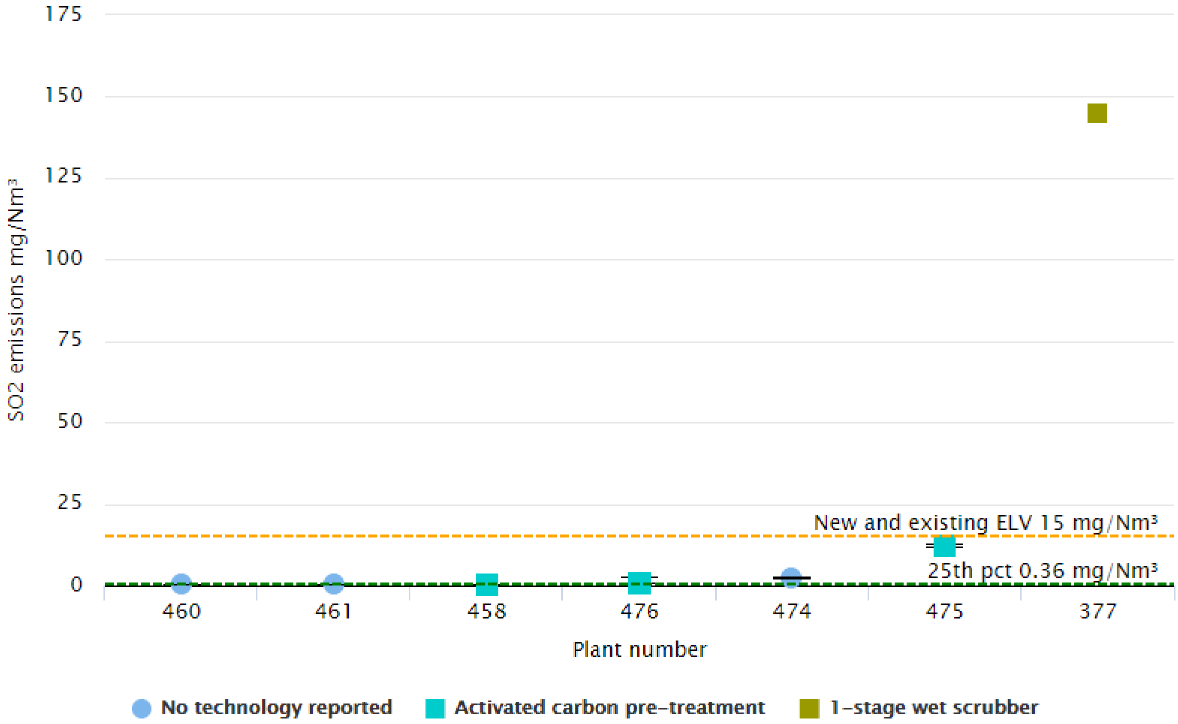
The other gaseous fuel MCPD ELV has a number of exceptions for different types of fuels and plants. For example, for dual fuel engines in gas mode, the ELV is doubled to 380 mg/Nm^3, which is closer to the performance of the majority of plants, though the two plants which have confirmed to be dual fuel engines seem to have the lowest emissions. Whilst there are different fuels, this factor does not seem to have a clear impact on performance e.g. there are biogas MCPs with low and high values in this sample.

The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with load factor nor size. There is a mild positive trend of emissions with plant size. Higher nitrogen content in fuel does not generate higher emission values.

3.1.9.5 SO_2 emissions from other gaseous fuel engines

Figure 3-38 shows that the vast majority have very low SO_2 emissions, but there are some outliers. Two abatement technologies were reported: treatment with activated carbon and scrubbers. 83% of plants in this sample achieve the ELV. All of these engines operate at high speed with spark ignition.

Figure 3-38 SO_2 emissions from other gaseous fuel engines

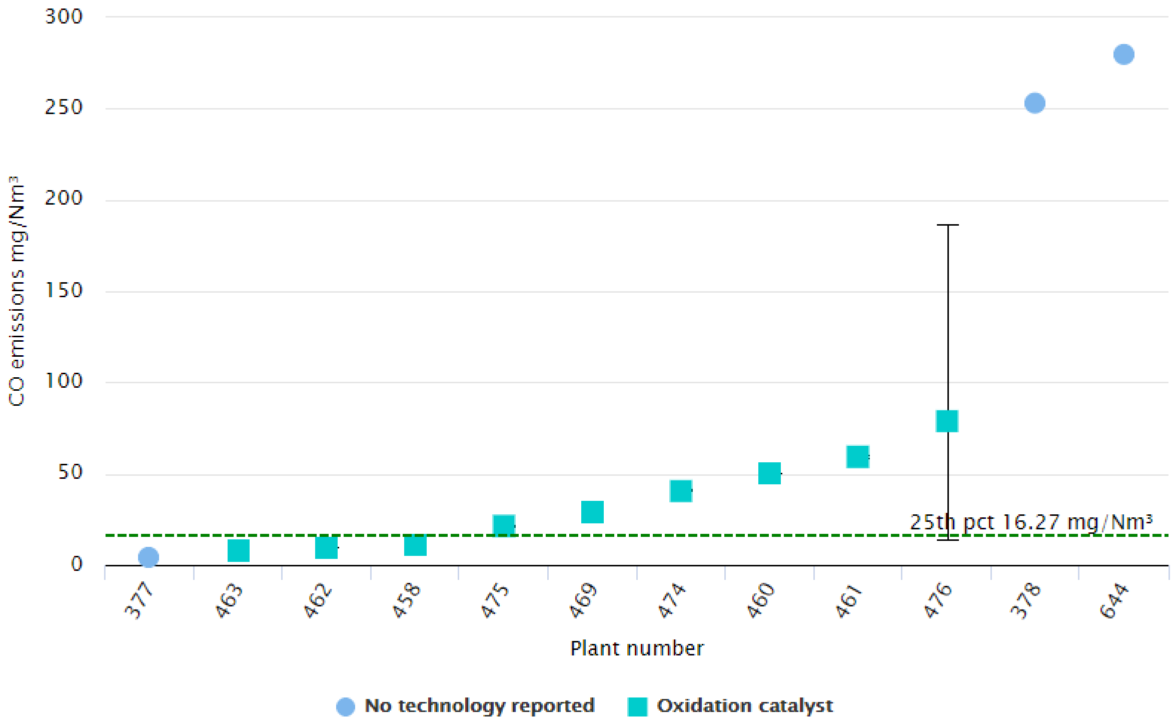


Due to the low sample size, the root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of plant age, load factor, size or fuel characteristics.

3.1.9.6 CO emissions from other gaseous fuel engines

Figure 3-39 shows the CO emissions from other gaseous fuel engines. No ELVs are available for CO, and due to the different fuels used in this category, no indicative value can be applied either (from LCP BREF). Only oxidation catalyst was used by MCPs to reduce CO emissions.

Figure 3-39 CO emissions from other gaseous fuel engines

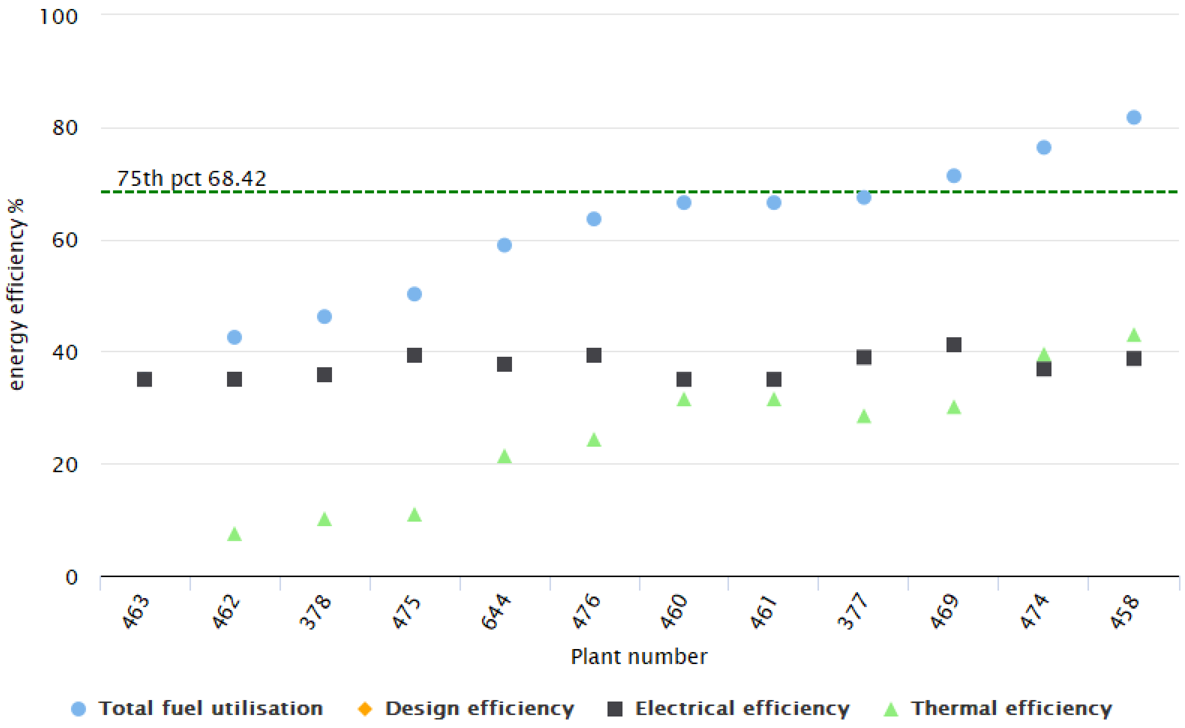


The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with plant age or size. Load factor shows a relatively high correlation with CO emissions. However, due to the small sample size, this is not a very robust conclusion, and it can therefore not support load factor as being a definite root cause of CO emissions for this category.

3.1.9.7 Energy efficiency of other gaseous fuel engines

Figure 3-40 shows the energy efficiency of other gaseous fuel engines. The 75th percentile value lies at 69% total fuel utilisation. There is only a small sample, but it shows a large variation in reported efficiency. Most plants are CHP providing 7-43% thermal efficiencies range and 35-41% on electrical efficiencies. There is still considerable variation visible, a large part of which is likely due to the different types of fuels that are in this category, such as coke oven gas or biogas.

Figure 3-40 Energy efficiency of other gaseous fuel engines



The root cause analysis (Steps 4 and 5) yielded no conclusive evidence of a strong relationship of emission values with load factor or size. There is a strong correlation of plant age with total fuel utilisation, making it a strong candidate for a possible root cause. However, due to the low sample size, this could also be spurious due to the types of fuel that could be used by this category.

3.1.10 Performance across all plant categories

3.1.10.1 NO_x and CO versus load factor

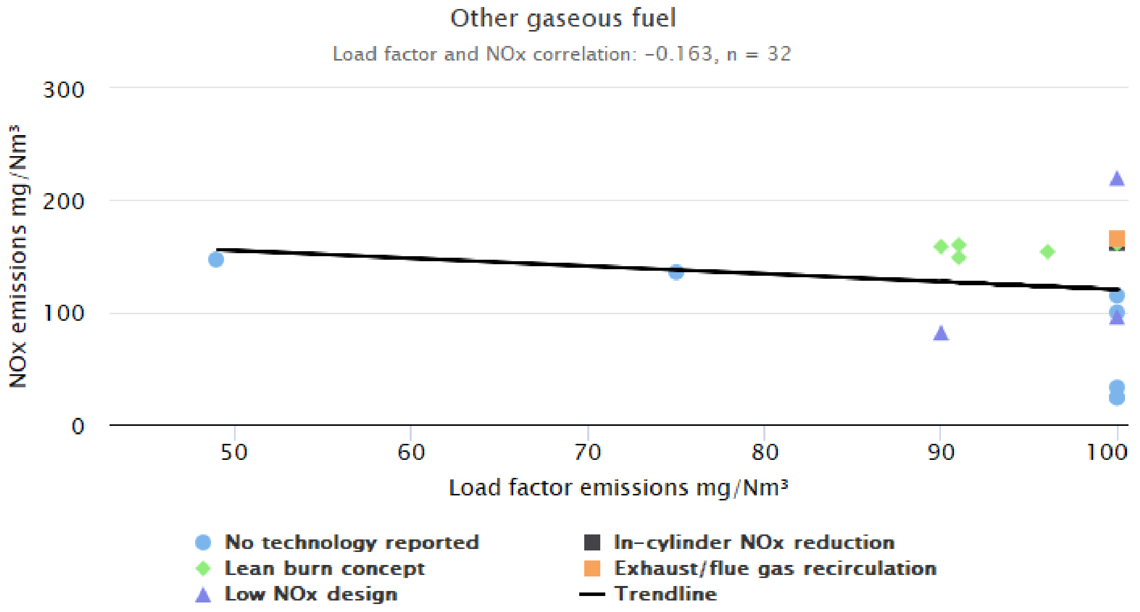
This report provides **for every MCP type a specific analysis of NO_x versus load factor and CO vs load factor**: this is summarised in the previous sections (section 3.1.4 to 3.1.9) and is also available in greater detail in Appendix 1 inside the interactive html file. This section brings all of this data together to compare across plant categories. Each variable is plotted on a scatter graph, and a trendline and accompanying correlation coefficient is calculated.

In this section, data was aggregated to obtain enough data for robust correlation charts. A sufficiently large sample size is required, to prevent situations where any one data point exerts too much leverage on the correlation. To establish whether a correlation is meaningful, the distribution of points around the trendline on each chart has to be normal. If not, then the correlation may be spurious, and any high correlation coefficient would become misleading. The distributions of the correlations of CO vs NOx or NO_x/CO with load factor are often not very normal. This property has not been tested statistically, instead the assessment of the viability of a correlation was done purely on visual analysis.

NOx vs load factor

Error! Reference source not found. shows the collection of correlations between NO_x and load factor for the other gaseous fuel category. The load factor is the ratio of the energy that the plant has produced over a period divided by the energy at reference power capacity over that period. For example, a load factor of 70% means that the plant was operated at 70% of maximum capacity over the emission measurement period. In some cases, respondents have indicated 0 values in the load factor field. This is an obvious error, and these plants have not been included in the sample for this analysis of NO_x vs load factor. The figure shows the variable distribution around the trendline, which means that no relationship between load factor and NO_x can be inferred. The other fuel categories also show no correlation.

Figure 3-41 Correlations of NOx emissions with load factor for other gaseous fuel, showing the heteroskedastic distribution of the data.



CO vs load factor

Some categories still only had a very small sample size of CO emissions, such as ‘other solid fuel’, ‘gas oil’, ‘other liquid fuel’ and ‘other gaseous fuel’. Many low CO emissions values were reported when operating below 70% load with most of these values. There are no plants reporting high CO emission levels which have oxidation catalysts applied.

These data challenges mean that for any of the fuel categories, similar to NO_x, it could not be shown that there is a correlation between CO and load factor. While literature suggests that this should be the case, it will not necessarily be observed in a cross-sectional study. CO and load factor are variables that can be influenced by many other variables. Time series data with the same plants should be better able to observe changes in CO with load factor, as other influencing variables can be held constant. The figures which show the lack of correlations are available in Appendix 1.

3.1.10.2 CO versus NOx emissions

It is not possible to minimise at the same time emissions of NOx and CO in combustion units. When burning hydrocarbons, the ideal reaction would result in the formation of carbon dioxide (CO_2) and water (if no sulphur or nitrogen compounds are present). However due to incomplete combustion processes at CO is also formed. CO_2 and CO form an equilibrium (Boudouard equilibrium) which is strongly temperature dependent.

Therefore, it is important to achieve sufficiently high temperatures in the combustion process to ensure a low formation of carbon monoxide. However, the nitrogen content (78%) of combustion air also reacts during fuel combustion resulting in nitrogen oxides (NO_X). The content of nitrogen oxides formed is also highly temperature dependent, as with higher temperatures more nitrogen oxides are formed. The resulting NO_X emissions are therefore called thermal NO_X (which are not related to possible NO_X emissions resulting from nitrogen compounds present in the fuel). To control the emissions of CO and NO_X at the same time it is therefore important to perform the combustion in a controlled temperature window.

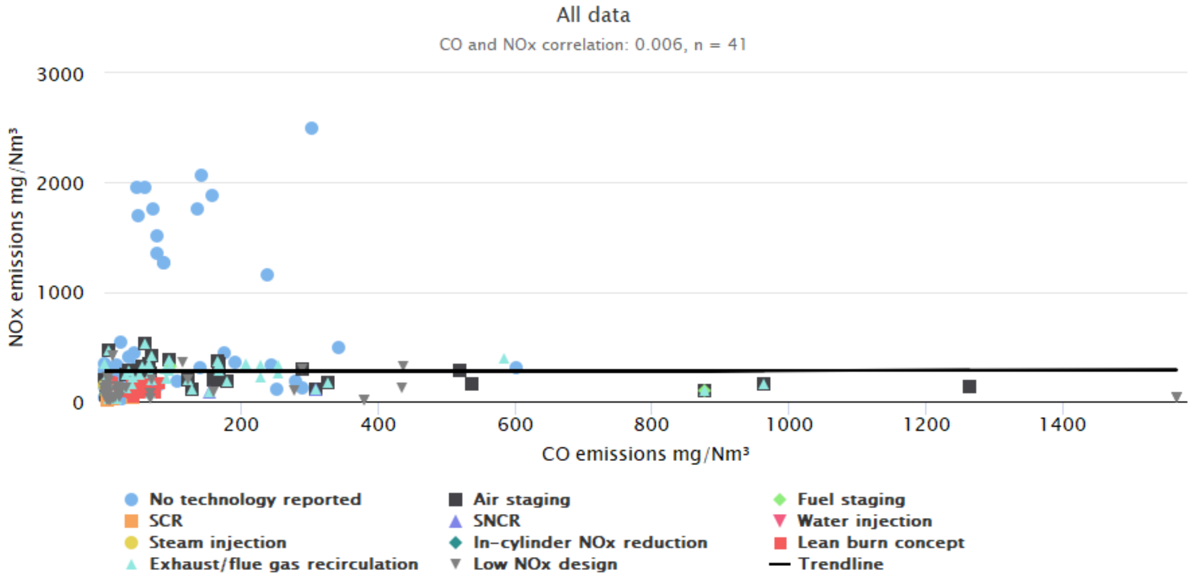
As a result, for any combustion unit there are generally trade-offs between low NO_X emissions, low CO emissions and a high energy efficiency. There are three main approaches to these trade-offs that may come into play, depending on regulations and economics.

- One approach is to **control for lowest NO_X** accepting a fuel efficiency penalty and possibly higher CO and hydrocarbon emissions.
- A second option is finding an **optimal balance between emissions and efficiency**.
- A third option is to **design for highest efficiency** and use **post-combustion waste gas treatment** to control emissions if required for environmental regulation purposes.

Regarding the MCPs that have provided data for this information exchange, most of them seem to be adopting a hybrid approach (second option above) as only a **limited number of them appear to be minimising NOx by generating very high CO emission levels**.

CO vs NO_x emissions are shown in Figure 3-42 for all plant categories. Data with very high NOx emission levels is seen for MCPs not using abatement technologies and only a few plants report very high CO and low NOx levels.

Figure 3-42 Correlations of CO emissions with NO_x emissions for all MCPs

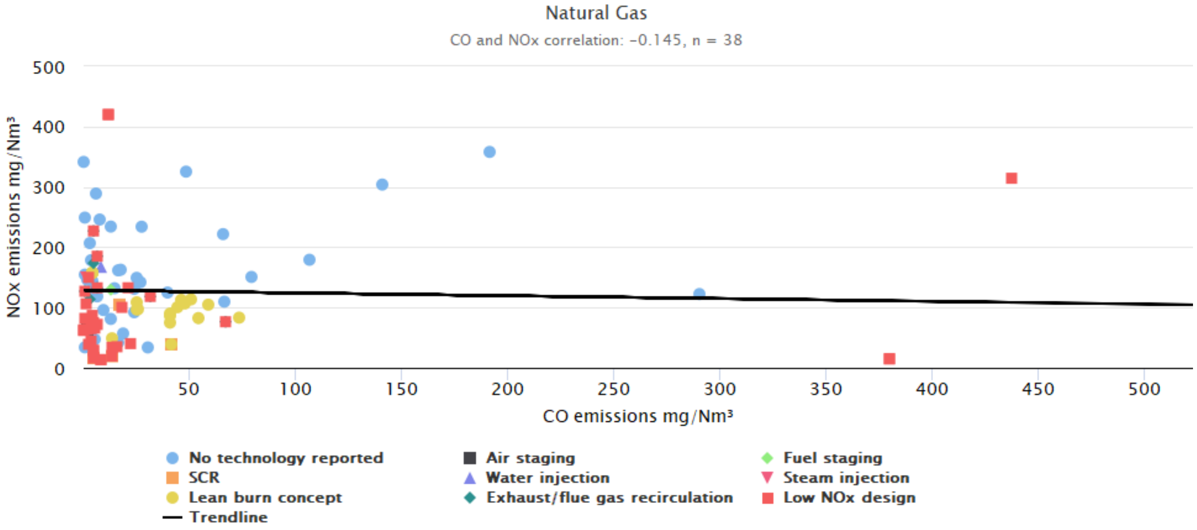


A complete data analysis per plant category and abatement technology is provided in Appendix 1 of this document.

Figure 3-43 shows the same data but only for natural gas plants. It cannot be concluded from the data that a relationship is present between CO and NOx. It seems that other compounding factors, such as plant design, fuel differences and operating differences, may mask the expected negative correlation between CO and low NO_x levels. MCPs appear to be using a range of different strategies (some minimising CO and other seeking compromise between CO and NOx).

Examples of a few plants minimising NOx at the cost of high CO emissions are #546 and #547 (38 mg/Nm^3 of NOx but CO >1400 mg/Nm^3) or #543 (15 mg/Nm^3 of NOx but CO >350 mg/Nm^3). These three plants all employ 'low NO$_x$ design'. See the equivalent for Figure 3-43 in Appendix 1 to see individual technologies employed by the plants in the scatter graph.

Figure 3-43 Correlations of CO emissions with NO$_x$ emissions in natural gas engines, boilers and turbines, highlighting plants with a low NO$_x$ design. The x-axis has been cropped to show more data, meaning plant #546 (CO 1400 mg/Nm^3) is not visible. Please see the figure in Appendix 1, section 4.2, for the full graph including this outlier and zooming capability.



Legend: "Low NOx design". MCPs using primary technologies such as DLN or LNB.

3.1.10.3 SIS & MIS performance versus grid –connected MCPs within the same plant categories

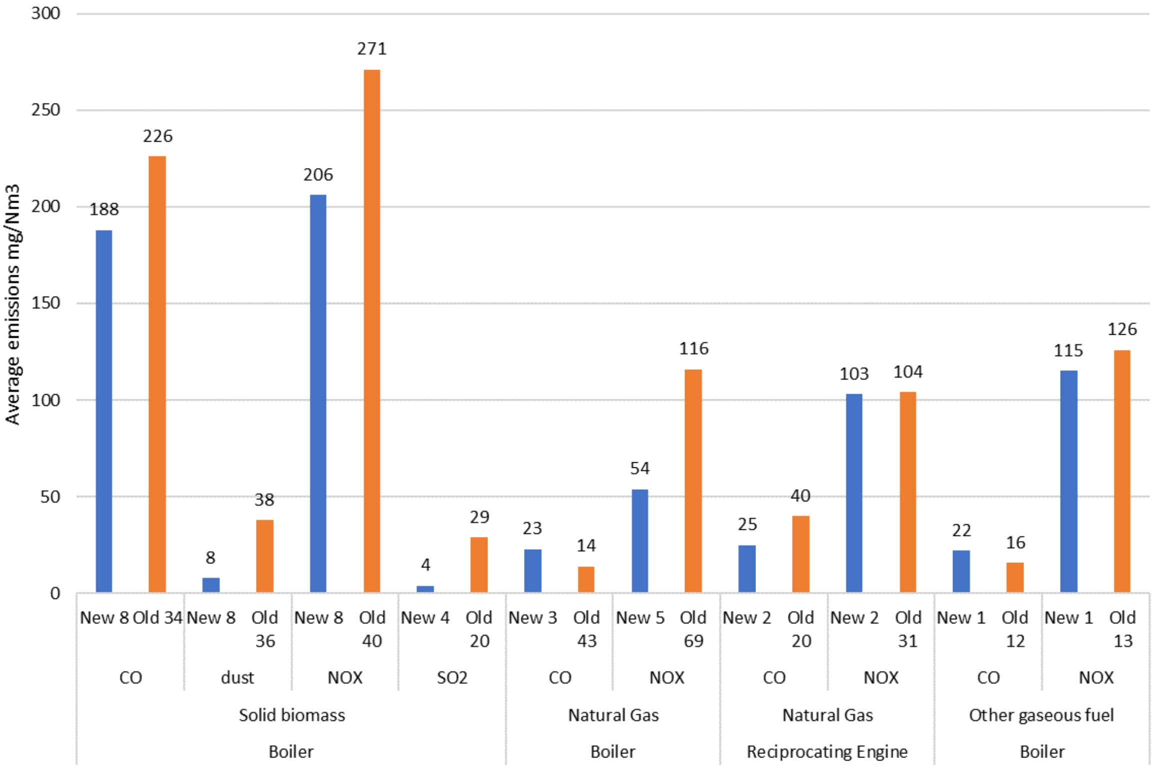
Combustion plants operating in Small Isolated Systems (SIS) and Micro Isolated Systems (MIS) benefit from certain dispensations with respect to the ELVs from the MCPD. As part of the MCP information exchange, the questionnaire included fields to capture whether the MCP plant was operating in a SIS or MIS. Out of 283 validated questionnaires, 17 included information for plants in a SIS or MIS. These 17 questionnaires contained environmental performance data from 2017 on the most common combustion configurations used in isolated systems (engines and gas turbines). Most of these plants are old and there were no new plants (commissioned since 2016) in this set. Only four plant categories in the MCP information exchange had questionnaires for both SIS/MIS and grid-connected MCPs. However, after further investigating these data points, some were not found to be SIS/MIS. After data cleaning, only 2 categories were remaining whereby the survey has data for both SIS/MIS and grid-connected plants. In these cases (solid biomass and other solid fuel) though, only 1 plant is SIS/MIS, which is not enough for a proper comparison. Therefore, no comparison could be made in this part of the analysis.

3.1.10.4 Performance of new plants versus rest plant categories

A categorisation is made in the data to define new plants as those that were built in 2016 or later. Only three categories have data from plants built in 2016 or later; solid biomass boilers, natural gas boilers, natural gas engines and other gaseous fuel boilers. The results are shown in Figure 3-44. 10 fuel-combustion-pollutant combinations had data that could be compared. The x-axis of the chart also shows the sample size for each bar after the label 'New' or 'Old' (whereby 'New 6' means 6 plants worth of data was used for the average).

The data in the figure shows a consistent trend across almost all categories that new plants have lower average emissions than older plants. The only exception to this was CO emissions for natural gas boilers and CO emissions for other gaseous fuel boilers. This could be due to a focus on NO_x reduction for new gas boilers, which may increase CO emissions. However, this relationship couldn't be explored further as there is not enough data available for new plants for a robust analysis.

Figure 3-44 Comparison of average emissions performance across categories with new plants (commissioned 2016 onwards)



3.2 Comparing optimal performance range with data from literature

3.2.1 Introduction

The following section shows how the performance of MCPs included in the information exchange compares to values from other sources. For each plant category, the analysis compares the median, minimum and maximum emissions from each source. As there is only very limited information on CO levels from different sources including the information exchange, and there are few ELVs set, this exercise is not done for CO. The sources included in the comparison include the following:

i. Emission limit values that apply to the plant category

ii. The survey data from this study

iii. Reference emission values from design data on combustion plants sourced from manufacturers and operators (only available for solid biomass boilers and natural gas turbines). The data concerns the expected flue gas concentration (mg/Nm^3) of the plant as designed after applying emission reduction technologies.

iv. Reference emissions values from performance data on emissions of plants from literature and the LCP BREF [10].

---

[10] For example, Table 5.40 in LCP BREF p463 shows performance data for plants burning solid biomass

Firstly, the survey data and reference values are compared to the ELVs available for this category. Information on ELVs was collected from the Netherlands, Belgium, Poland, Austria and Sweden, and the most stringent limit value is the most ambitious benchmark against which plant performance can be compared to. The MCPD is also included as there are cases whereby the Member States mentioned earlier have not set a more stringent ELV than exists in the MCPD. These most stringent ELVS are shown in Table 3-2. Note that this is not intended as a comprehensive overview of the most stringent ELVs across the EU, rather it is an indicative overview based on ELVs from Member States which are known to have stringent regulations in place. The goal is to understand how plants that apply certain abatement technologies compare to reference data and a set of known stringent ELVs, to aid in selection of b available technologies.

Table 3-2 EU wide most stringent ELVs for each of the relevant categories. Categories 9 – 11 (Multi-fuel plants) are not included.

Category	Pollutant	Value (mg/Nm^3)	Issuer	Comment
1 Solid biomass boilers	NO_x	145	NL[11]	Applies to plants of size 5 – 50 MW. 275 mg/Nm^3 for plants of size 400 kW – 5 MW.
	SO_2	200	NL	
	Dust	5	NL	
	CO	220	DE	150 at 11 % O2, Only applies to untreated wood
2 Other solid fuel boilers	NO_x	100	NL	
	SO_2	200	NL	
	Dust	5	NL	
	CO	160	DE	
3 Gas oil boilers	NO_x	120	NL	
	SO_2	170	DE	ELV is to be reached with low S fuel (< 0.1% S) or an equivalent measure
	Dust	5	NL	
	CO	80	DE	Existing plants < 10 MW: 150
4 Gas oil Engines	NO_x	190	MCPD	No ELVs were found in consulted authorities lower than the MCPD
	CO	113	DE	300 at 5 % O2
5 Gas oil Turbines	NO_x	75	MCPD	For new plants only
	CO	100	DE	load ≥ 70 %
6 Other liquid fuel Boilers	NO_x	150	BE	150 mg/Nm^3 for plants of size 20 – 50 MW. For other sizes the Belgium values are 400 mg/Nm^3 (5 – 20 MW), 525 mg/Nm^3 (2 – 5 MW) and 185 mg/Nm^3 (1 – 2 MW)
	SO_2	200	NL	
	Dust	20	MCPD	20 mg/Nm^3 for plants of size 5 – 50 MW. 50 for plants of size 1 – 5 MW.
	CO	80	DE	
7 Other liquid fuel Engines	NO_x	150	NL	
	SO_2	65	NL	
	Dust	3	AT	Existing plants only. New plants the most stringent confirmed ELV is 10 mg/Nm^3 plants of size 20 – 50 MW, and 20 mg/Nm^3 for size 1 – 20, both from NL.
	CO	113	DE	

---

[11] Netherlands MCP limit values do not discriminate between new or existing plants. Existing plants are only given more time to adapt to new regulations.

Category	Pollutant	Value (mg/Nm^3)	Issuer	Comment
8 Other liquid fuel Turbines	NO_x	50	NL	
	SO_2	57	DE	ELV is to be reached with low S fuel (< 0.1% S) or an equivalent measure
	Dust	5	NL	
	CO	100	DE	load ≥ 70 %
12 Natural Gas Boilers	NO_x	70	NL	
	SO_2	10	DE	Applies to fuel from the public gas supply
	Dust	5	BE/DE	
	CO	50	DE	
13 Natural Gas Engines	NO_x	35	NL	
	SO_2	3	DE	(10 at 3 % O2)
	CO	94	DE	(250 at 5 % O2), Applies to fuel from the public gas supply and liquid gases (LNG, LPG)
14 Natural Gas Turbines	NO_x	50	NL	MCPD also has this limit value, but only for new plants.
	SO_2	12	BE	
	CO	100	DE	Applies to fuel from the public gas supply
15 Other gaseous fuel Boilers	NO_x	70	NL	
	SO_2	5	PL	Only known to apply to existing plants
	Dust	5	BE	
	CO	80	DE	Non-public gas supply fuels
16 Other gaseous fuel Engines	NO_x	35	NL	Exceptions exist for biogas (115 mg/Nm^3) and for small plants (1 – 2.5 MW) on natural gas, propane or butane (90 – 115 mg/Nm^3). All are still more ambitious than lowest MCPD (190 mg/Nm^3)
	SO_2	15	MCPD	NL only mention the MCPD exception for biogas (40 mg/Nm^3) in their legislation.
	CO	188	DE	(500 at 5 % O2) for biogas, sewage gas, mine gas, wood gas
17 Other gaseous fuel Turbines	NO_x	50	NL	
	SO_2	15	NL	
	CO	100	DE	Non-public gas supply fuels, load ≥ 70 %

On the data collected that is compared to the ELVs, a further sub categorisation is made based on technologies used by the plants in the survey (information exchange) and the reference plants. For example, see Figure 3-45 in Section 3.2.2 on NO_x emissions from solid biomass boilers, where a further 7 sub categories are identified. For the survey data, these are: air staging, fuel staging, low NO_x burner, flue gas recirculation and SNCR. For the design data, only SNCR was mentioned. Categories in the figures with NA in the x-axis label mean that this statistic is made from plant data with no further information on abatement technologies applied.

The figures in the following sections show median values in blue with accompanying minimum and maximum values. Only categories are shown for which data is available. Absolute minimum and maximum values are used from the data on performance, design and limit values. For the survey data (i.e. that collected as part of the information exchange), the 5th and 95th percentile values are used instead. This is done because of the outliers in the data that are identified in Section 3.1, often leading to zero emissions as the minimum and very high values as the maximum, which are not considered representative of the plant categories concerned. Lastly, the sample size for each of the categories is also shown to aid in assessing the confidence in the summary statistics. In the case of the ELVs, this number displays the number of authorities (Member States as well as the MCPD itself) which have ELVs on this category. ELVs for CO are found in some Member State legislation and displayed in Table 3-2, but a comparison has not been included here as there are no ELVs for CO in the MCPD.

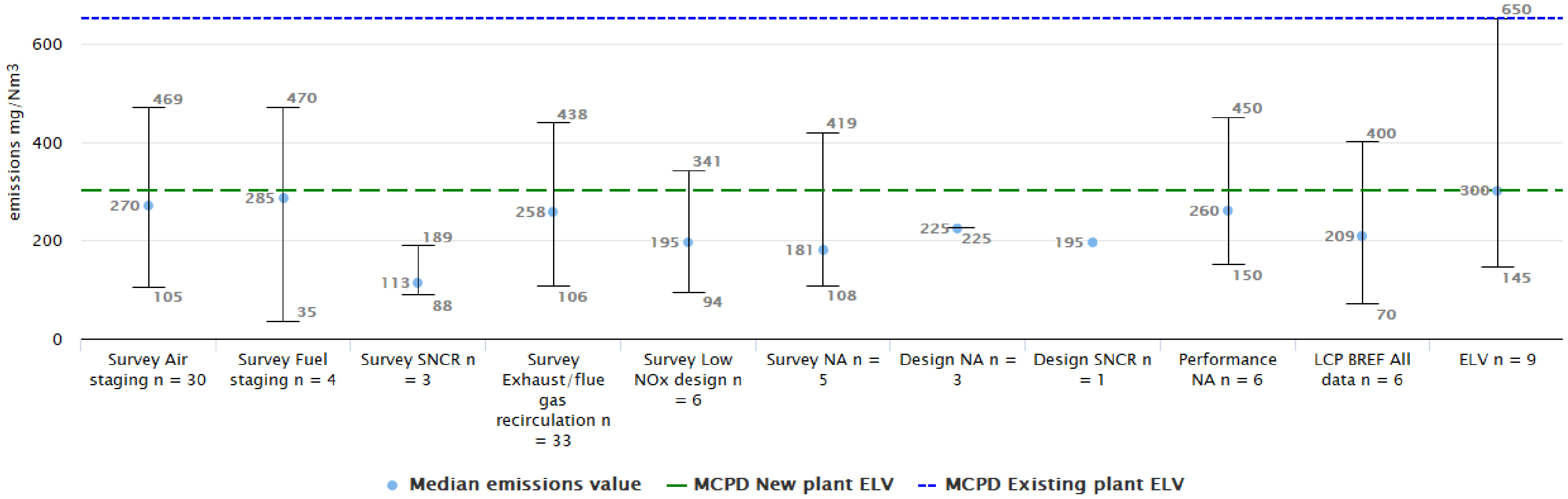
Note: Fuel quality and composition also has an impact (e.g. higher sulphur content leading to higher SO_2 emissions). This impact has been reviewed in section 3.1 of this document (described separately for each category, where relevant) and not revisited in this section 3.2.

3.2.2 Solid biomass plant data vs references

NO_x emissions

Figure 3-45 shows the results of the comparison of data sources of NO_x emissions for solid biomass boiler plants. Each ‘n = ‘ number shows the number of data points used to construct the median, minimum and maximum values. This also includes ELVs, n = 9 means 9 distinct ELVs from different countries were used to construct the data. The information shows a large variation in limit values of 145 to 650 mg/Nm^3, covering existing and new plants. The MCPD is at the median of 300 mg/Nm^3, with exception to 500 mg/Nm^3 for plants of size 1 – 5 MW. As shown in Table 3-2, the minimum limit value is 145 mg/Nm^3 from the Netherlands. From the survey data, plants that employ air staging, fuel staging, SNCR, a low NOx design[12] and exhaust/flue gas recirculation all have a minimum value (5th percentile of the sample) that can meet this most ambitious emissions limit value (ELV). Reference ELV from design data was available for four plants, though only one of these specified the application of an abatement technology (SNCR), which did not bring its design value (195 mg/Nm^3) below the most ambitious ELV of 145. Reference ELV from performance data from literature for six plants also has had no information on abatement technologies applied (NA), though the minimum value of the performance category (150) does get very close to the minimum ELV. From this figure therefore, it can be concluded that even the most ambitious limit value can be met by applying a wide range of technologies.

Figure 3-45 Comparison of median, minimum and maximum values of various sources for NOx emissions from solid biomass boilers.



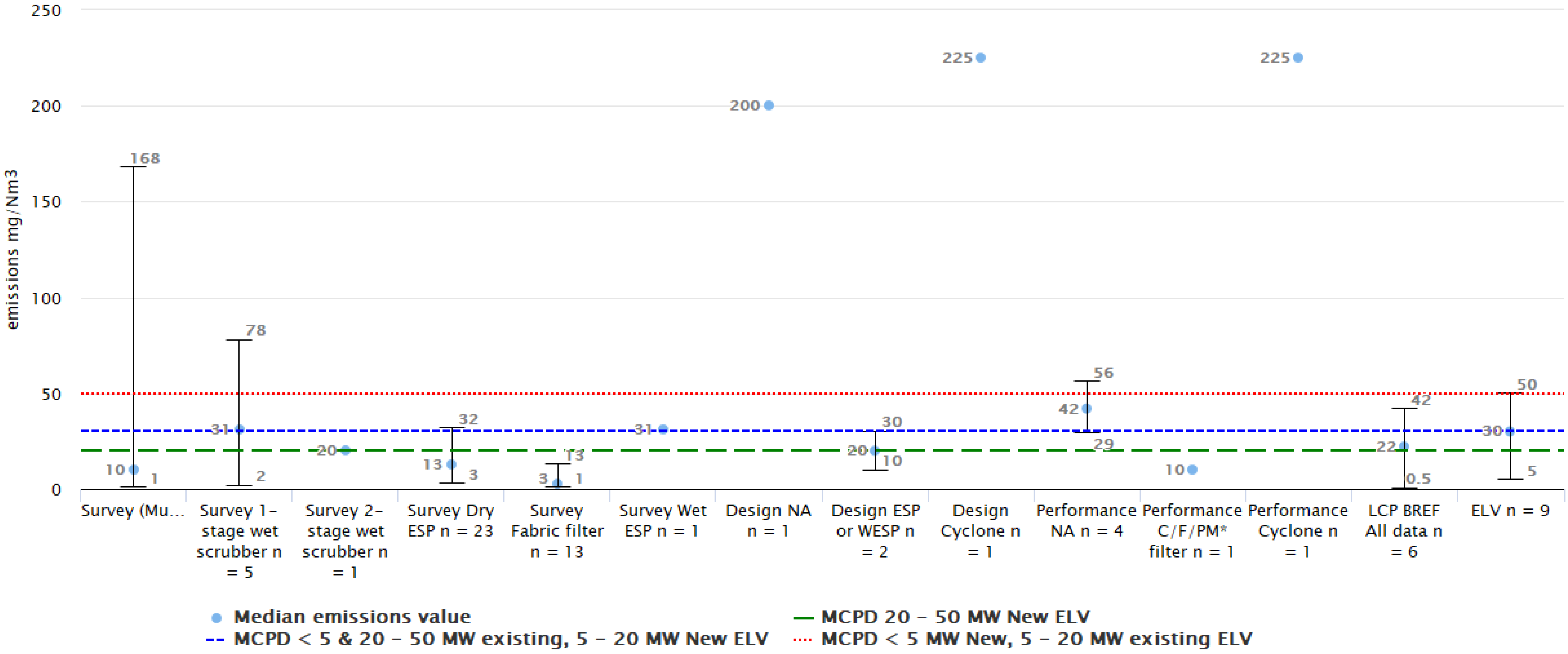
---

[12] ‘Low NO_x design’ includes the questionnaire categories ‘Low NOx burner, Low NOx combustion, Ultra Low NOx combustion and Dry Low NOx (DLN).

Dust emissions

Figure 3-46 shows the results of the comparison of data sources of dust emissions for solid biomass boiler plants. The variation in limit values is not high at 5 – 50 mg/Nm^3. The MCPD value is 20 mg/Nm^3 with exception to 30 mg/Nm^3 for size class 5 – 20 MW and 50 mg/Nm^3 for size class 1 – 5 MW. As shown in Table 3-2, the minimum limit value is 5 mg/Nm^3 from the Netherlands, which applies to all plants above 5 MW (it is 20 mg/Nm^3 for class 1 – 5 MW). From the survey data, plants that employ a cyclone, wet scrubber, fabric filter or dry ESP can meet or get very near the most stringent limit value. This conclusion is supported by the design and performance data from literature. Other references(literature) for cyclones show higher values well above ELVs.

Figure 3-46 Comparison of median, minimum and maximum values of various sources for dust emissions from solid biomass boilers

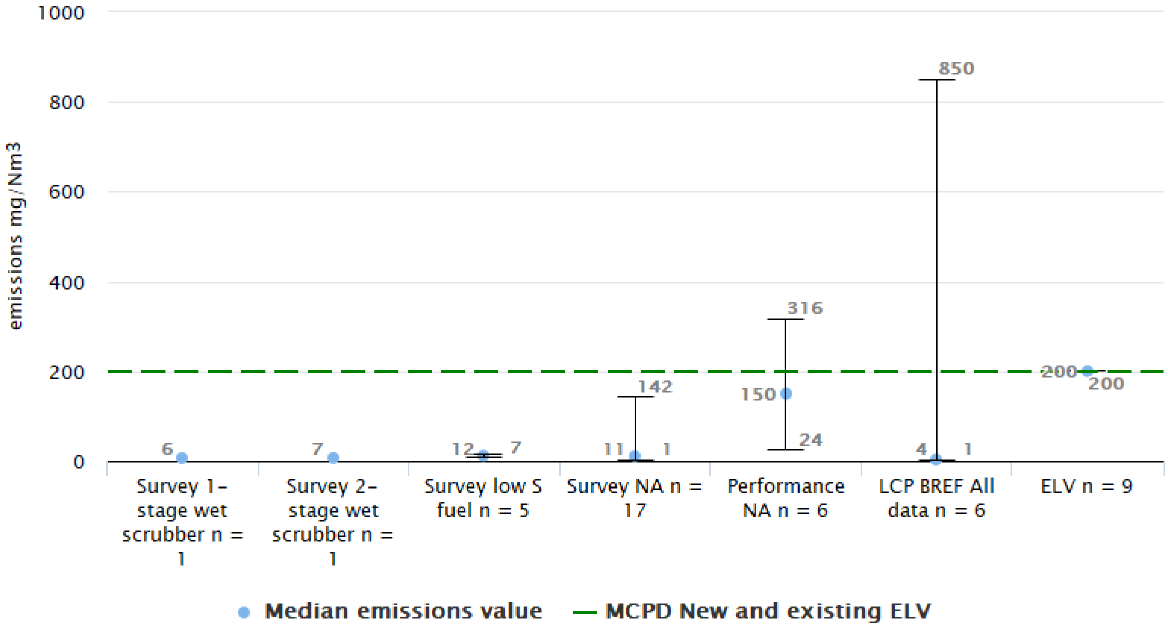


* C/F/PM = Ceramic, fabric or particulate filter

SO_2 emissions

Figure 3-47 shows the results of the comparison of data sources of SO_2 emissions for solid biomass boiler plants. The information shows no variation in limit values (MCPD: 200 mg/Nm^3, with exception to 500 mg/Nm^3 for plants of size 1 – 5 MW, not shown). As shown in Table 3-2, the minimum limit value is 200 mg/Nm^3 from the MCPD. This value is also used by all other Member States for which the comparison was made, and therefore there is no variation visible in the figure on the ELVs. From the survey data, plants that employ a wet scrubber and/or use cleaner fuels (sulphur < 0.05 %) can all readily meet this limit value, though even for the sample of eight plants for which no abatement technology was reported (Survey NA), the median at 9 is far below the limit value. Finally, performance data from literature for six plants shows large variation but the median and minimum values are well below the minimum ELV.

Figure 3-47 Comparison of median, minimum and maximum values of various sources for SO_2 emissions from solid biomass boilers

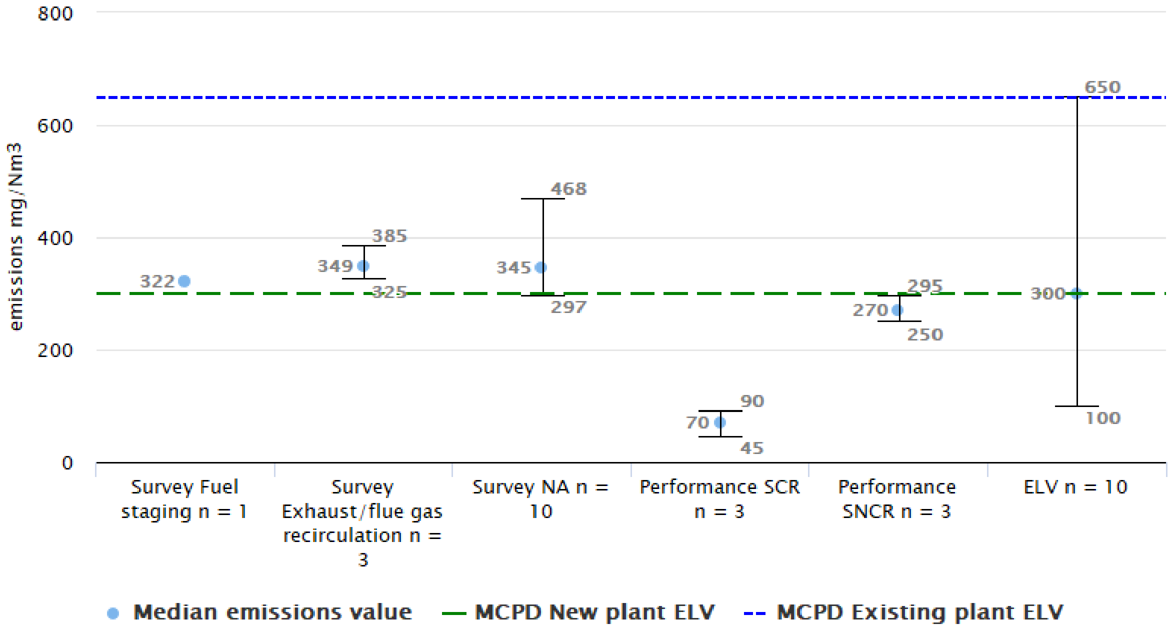


3.2.3 Other solid fuel plant data vs references

NO_x emissions

Figure 3-48 shows the results of the comparison of data sources of NO_x emissions for other solid fuel boiler plants. The information shows a large variation in limit values of 100 to 650 mg/Nm^3. The MCPD is at the median of 300 mg/Nm^3, with exception to 500 mg/Nm^3 for plants of size 1 – 5 MW. As shown in Table 3-2, the minimum limit value is 100 mg/Nm^3 from the Netherlands. From the survey data, plants using fuel staging, exhaust/flue gas recirculation or no technology are not able to meet this most stringent ELV. Performance data from literature was available for six plants. Only SCR is able to meet the most stringent limit value, and other technologies such as SNCR and fuel staging are not able to allow these plants to meet the most stringent ELV.

Figure 3-48 Comparison of median, minimum and maximum values of various sources for NO_x emissions from other solid fuel boilers.



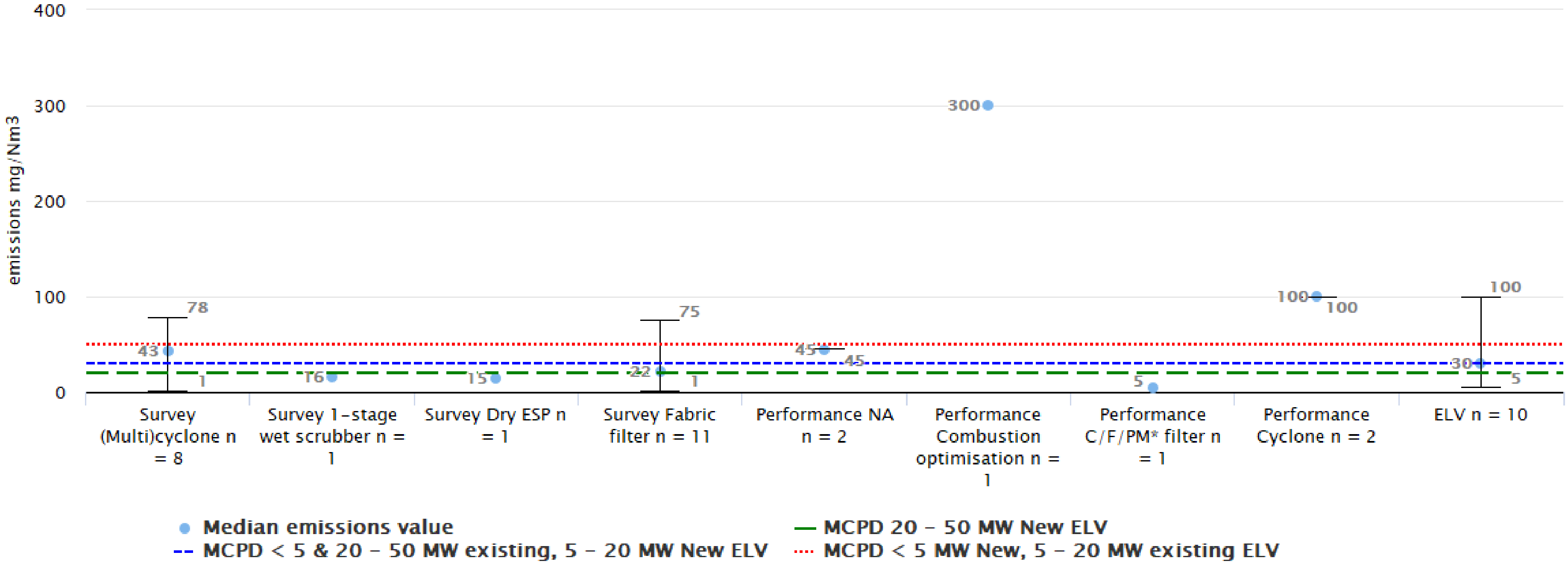
.

Dust emissions

Figure 3-49 shows the results of the comparison of data sources of dust emissions for other solid fuel boiler plants. The variation in limit values is relatively high at 5 – 100 mg/Nm³. The MCPD value is 20 mg/Nm³ for new plants 20- 50 MW, with existing plant ELVs at 30 mg/Nm³ for size class 20 – 50 MW and 50 mg/Nm³ for size 1 – 20 MW. As shown in Table 3-2 the minimum limit value is 5 mg/Nm³ from the Netherlands, which applies to all plants irrespective of size.

From the survey data, plants that employ a fabric filter can meet the most stringent limit value, though the variation in the 10 plants that use this technology is high, with the median at 29 mg/Nm³. This conclusion is supported by the performance from literature data, where the 1 reference value using a filter also meets the value at 5 mg/Nm³. Like the solid biomass boilers, emissions of reference plants using cyclones (not a technology found in the survey data) is relatively high, suggesting this is not an effective abatement technology for dust.

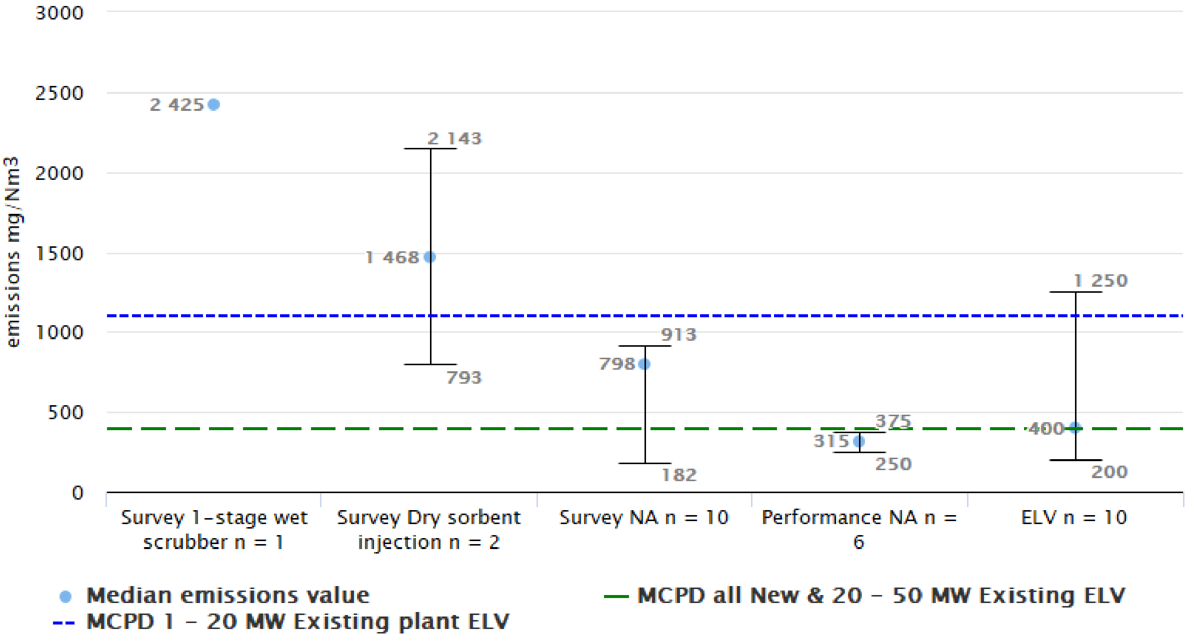
Figure 3-49 Comparison of median, minimum and maximum values of various sources for dust emissions from other solid fuel boilers.



SO$_2$ emissions

Figure 3-50 shows the results of the comparison of data sources of SO$_2$ emissions for other solid fuel boiler plants. The information shows a large variation in limit values (MCPD: 400 mg/Nm^3 for new plants, 1100 mg/Nm^3 for existing plants). As shown in Table 3-2, the minimum limit value is 200 mg/Nm^3 from the Netherlands. From the survey data, dry sorbent injection (also known as in-furnace desulphurisation) and wet scrubber do not meet MCPD nor most stringent ELV. Finally, performance data from literature for six plants shows low values though lack of information on potential abatement technologies used by these plants means no meaningful comparison is possible here.

Figure 3-50 Comparison of median, minimum and maximum values of various sources for SO$_2$ emissions from other solid fuel boilers.



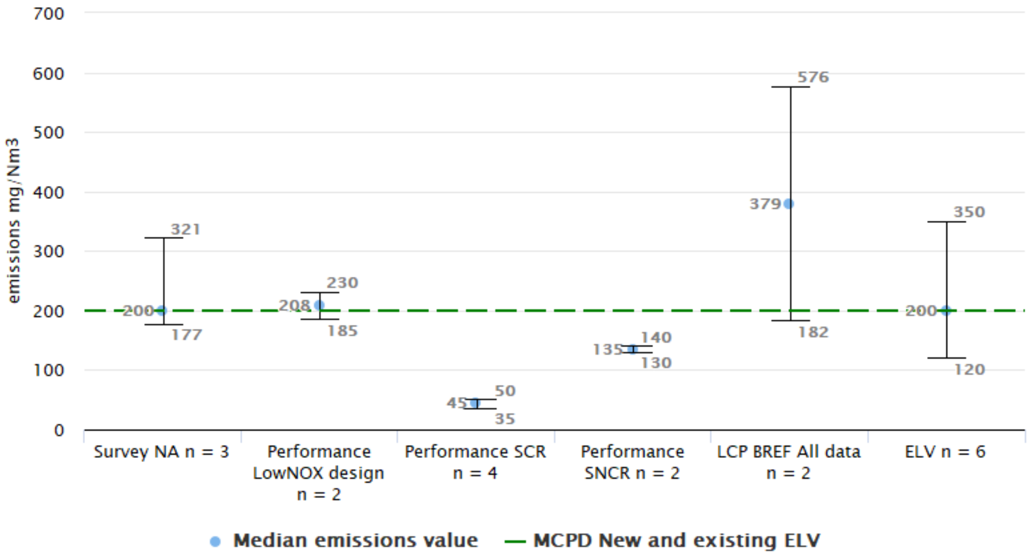
3.2.4 Gas oil plant data vs references

3.2.4.1 Gas oil boilers

NO$_x$ emissions

Figure 3-51 shows the results of the comparison of data sources of NO$_x$ emissions for gas oil boilers. The information shows a small variation in limit values of 120 to 200 mg/Nm^3. The MCPD is at the median of 200 mg/Nm^3, applicable to all plants new and existing. As shown in Table 3-2, the minimum limit value is 120 mg/Nm^3 from the Netherlands. Performance data from literature was available for six plants and shows that only SCR technology is able to meet the most stringent limit value, and SNCR falls short although does come close. From this figure therefore, it can be concluded that the most ambitious limit value can be met by applying SCR technology. Survey data using low NO$_x$ is close to the ELV of 200 mg/Nm^3.

Figure 3-51 Comparison of median, minimum and maximum values of various sources for NO_x emissions from gas oil boilers.



<u>Dust and SO_2 emissions</u>

No dust or SO_2 abatement technologies were reported by the survey sample on gas oil boilers, and therefore no meaningful analysis was possible for these pollutants.

3.2.4.2 Gas oil engines

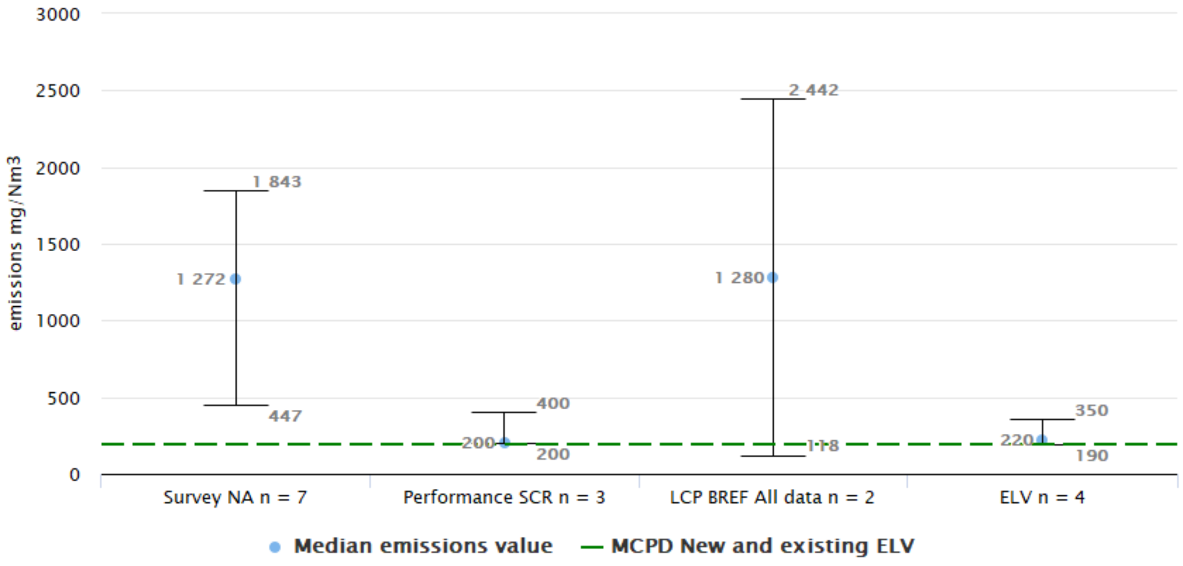
For this category, no SO_2 abatement technologies were reported by the survey sample, and therefore no meaningful analysis was possible for gas oil engines and turbines. Dust particle filters were reported by two italian plants (<10MWth) in the survey. The MCPD also does not provide ELVs for SO_2 or dust for this category.

<u>Regarding NO_x</u>, plant performance data from literature using SCR was available for engines, showing significantly lower emissions than those who do not use any technologies. These are also the only plants who meet the MCPD ELVs. The MCPD ELV is by default 190 mg/Nm^3, applicable to all plants new and existing, with exceptions[13] to 1850 mg/Nm^3. No engines specifically reported as dual fuel engines in the sample.

---

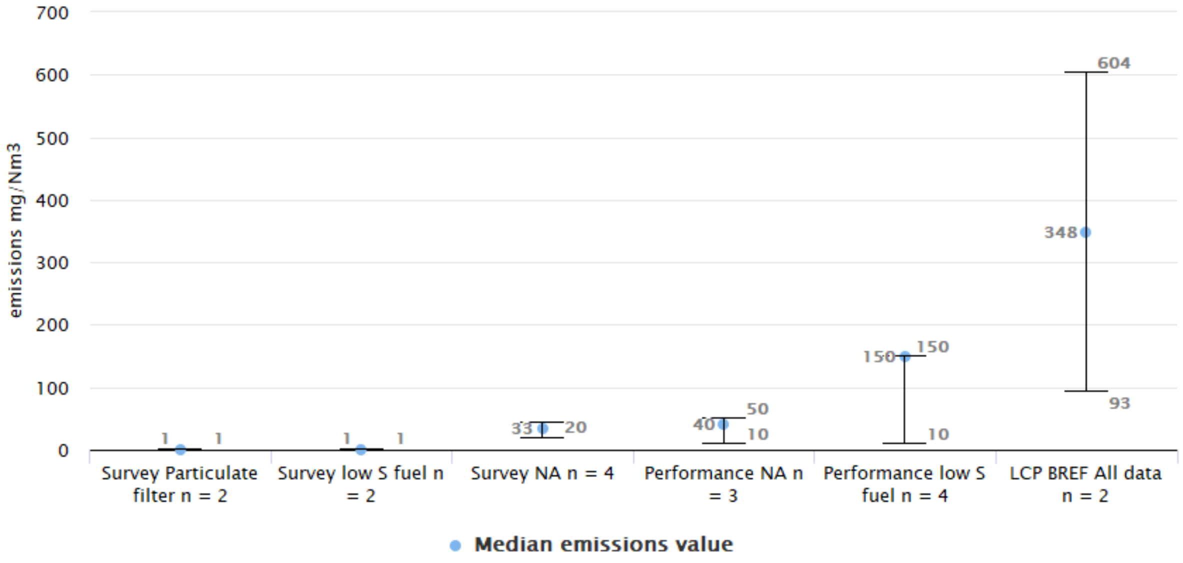
[13] Existing plants exception (i) where it is a) a dual fuel engine and b) operating in liquid mode (SIS/MIS doesn't matter) or (ii) a diesel engine the construction of which started before 18 May 2006. New plants exception (i) where it is a) SIS/MIS and b) a dual fuel engine and c) operating in liquid mode or (ii) where it is a) SIS/MIS and b) diesel engine with ≤ 1 200 rpm and c) with total rated thermal input above 20 MW

Figure 3-52 Comparison of median, minimum and maximum values of various sources for NOx emissions from gas oil engines



Regarding SOx: There is no MCPD ELV for SO_x so this comparison has not been made.

Figure 3-53 Comparison of median, minimum and maximum values of various sources for SOx emissions from gas oil engines



3.2.5 Other liquid fuel plant data vs references

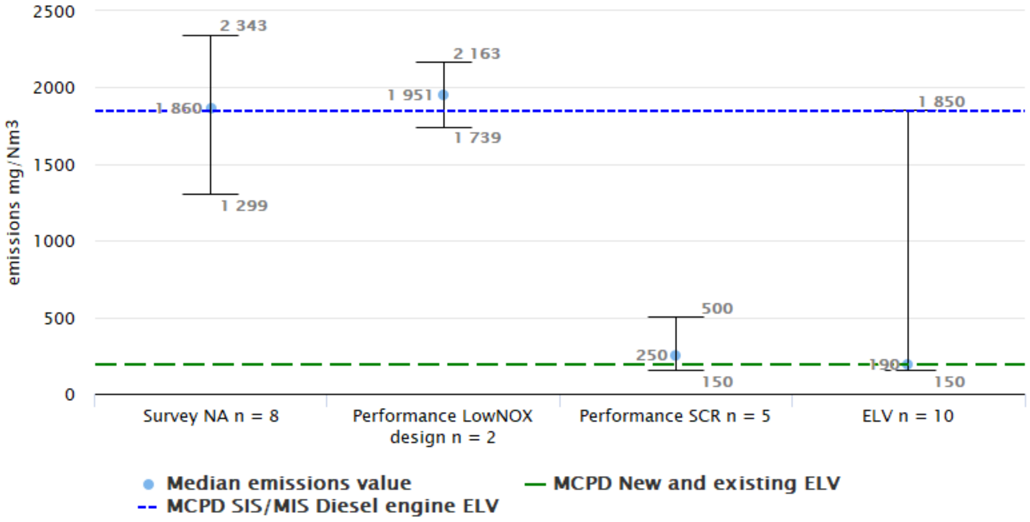
3.2.5.1 Other liquid fuel engines

NOx emissions

Figure 3-54 shows the results of the comparison of data sources of NO_x emissions for other liquid fuel engine plants. The information shows a large variation in limit values of 150 to 1850 mg/Nm^3. The MCPD is at the median of 190 mg/Nm^3, with exception to 1850 mg/Nm^3 for plants part of SIS or MIS, which is the least ambitious ELV in the data. As shown in Table 3-2, the minimum limit value is 150 mg/Nm^3 from the Netherlands. From the survey (questionnaires) data, no technologies were reported so only data for plants without specific abatement technologies mentioned is shown (Survey NA).

All survey plants are part of SIS/MIS. Performance data (from literature) for three plants that use SCR is available, and it can be seen that these reference values are far below even the minimum of the survey data and are able to meet the stringent ELV from the Netherlands. Without the use of abatement technologies, emissions of NO_x from SIS/MIS plants are high, though the minimum and median is around the MCPD SIS/MIS limit value of 1850 mg/Nm[3]. Performance data from literature prove that primary emission abatement technologies (such as low sulphur HFO or diesel and low NOx design (Miller) for NOx emissions) may deliver emission levels below the MCPD exception ELV.

Figure 3-54 Comparison of median, minimum and maximum values of various sources for NO_x emissions from other liquid fuel engines



Dust and SO_2 emissions

Neither the sample data nor the reference data for other liquid fuel engines supplied information about abatement technologies used, and therefore no meaningful conclusions can be derived.

3.2.5.2 Other liquid fuel boilers and turbines

The survey only contained data on 3 plants, of which only 1 remains after data cleaning for NO_x, SO_2 and dust. This category has therefore not been analysed here or in Section 3.1 as there is not enough data to derive meaningful conclusions. No data was supplied on any liquid fuel turbines in the survey.

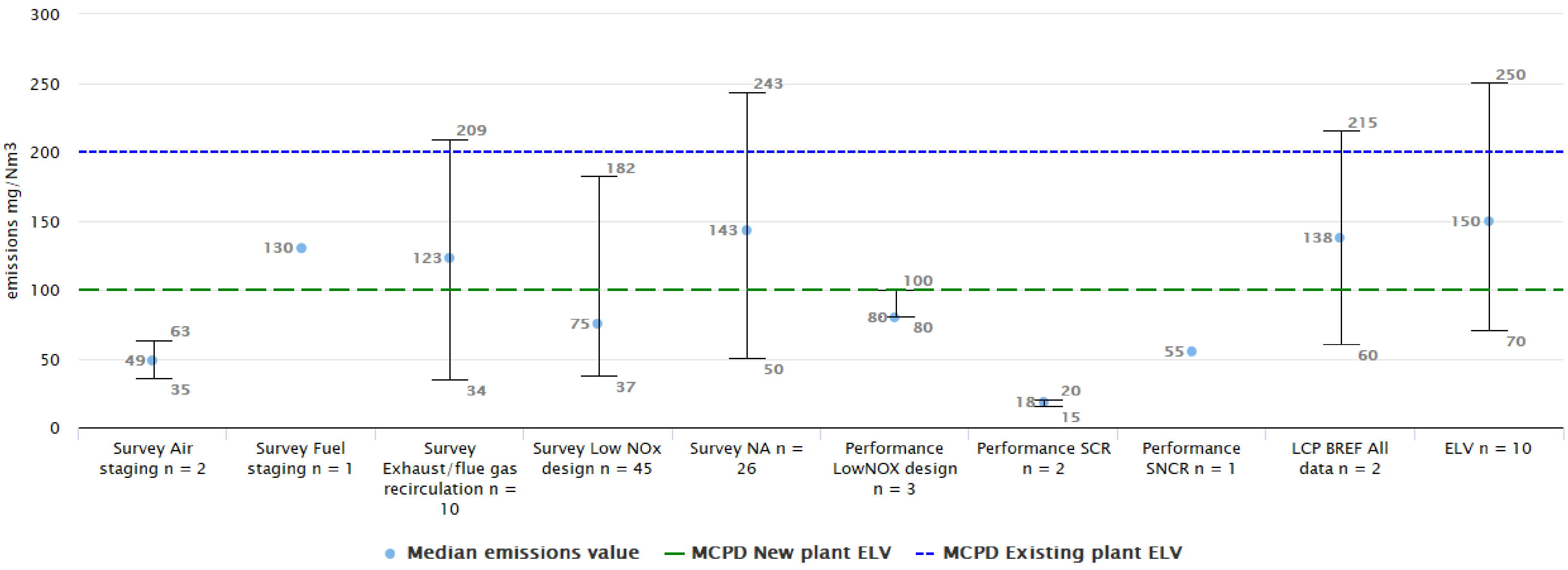
3.2.6 Performance of plants using natural gas vs references

3.2.6.1 Natural gas boilers

NOx emissions

Figure 3-55 shows the results of the comparison of data sources of NO_x emissions for natural gas boiler plants. The information shows some variation in limit values of 70 to 250 mg/Nm^3. The MCPD ELV is 100 mg/Nm^3 for new plants, and 200 mg/Nm^3 for existing plants with exception to 250 mg/Nm^3 for existing plants of size 1 – 5 MW. As shown in Table 3-2, the minimum limit value is 70 mg/Nm^3 from the Netherlands. From the survey data, plants that employ air staging, exhaust/flue gas recirculation or a low NO_x design have a minimum value that can meet the most stringent ELV, though only the median for air staging samples reach Dutch ELV. There is a much larger range for plants that reported no information on abatement technologies although the minimum does meet the most stringent ELV and the median is below the ELV median. Performance data from literature for six plants shows that applying SCR or SNCR can meet the stringent value and having a low NO_x burner performs very close to it at 80 mg/Nm^3.

Figure 3-55 Comparison of median, minimum and maximum values of various sources for NO_x emissions from natural gas boilers.



Dust and SO_2 emissions

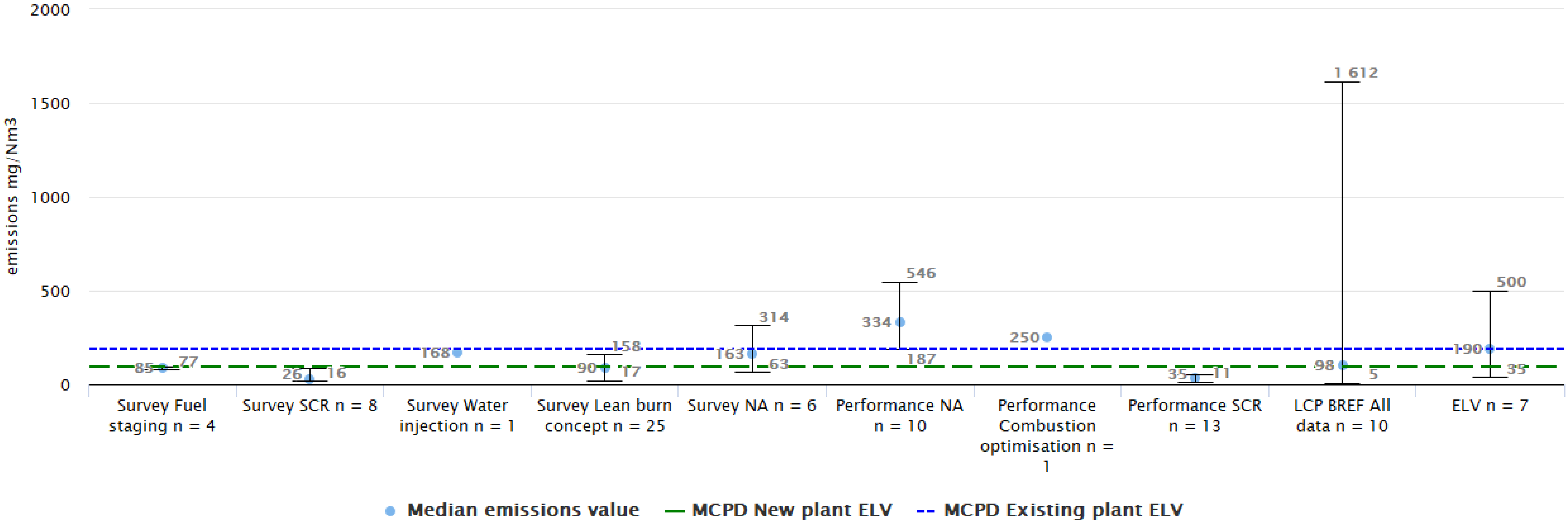
Neither the sample data nor the reference data for natural gas boilers have reported any abatement technologies used, and therefore no meaningful conclusions can be derived. This is also not an emissions category that is considered relevant for natural gas fired boilers.

3.2.6.2 Natural gas engines

NOx emissions

Figure 3-56 shows the results of the comparison of data sources of NO_x emissions for natural gas engine plants. The information shows significant variation in limit values of 35 to 500 mg/Nm^3. The MCPD ELV is 95 mg/Nm^3 for new plants, and 190 mg/Nm^3 for existing plants with exception for dual fuel plants in gas mode, for which the limit values are doubled. As shown in Table 3-2, the minimum limit value is 35 mg/Nm^3 from the Netherlands. From the survey data, plants that employ the lean burn concept and SCR are able to meet this most stringent ELV. Those using fuel staging in the survey meet the MCPD ELV. Performance data from literature from thirteen plants applying SCR is consistent with the survey and can be an effective way to meet the most stringent ELV at 35 mg/Nm^3. Among natural gas engine options, lean burn natural gas engines generate the lowest NOx emissions directly from the engine. It is called "advanced" when the system is tuned to achieve NOx levels below 100 mg/Nm^3 (15 % O_2).

Figure 3-56 Comparison of median, minimum and maximum values of various sources for NO_x emissions from natural gas engines.



Dust and SO_2 emissions

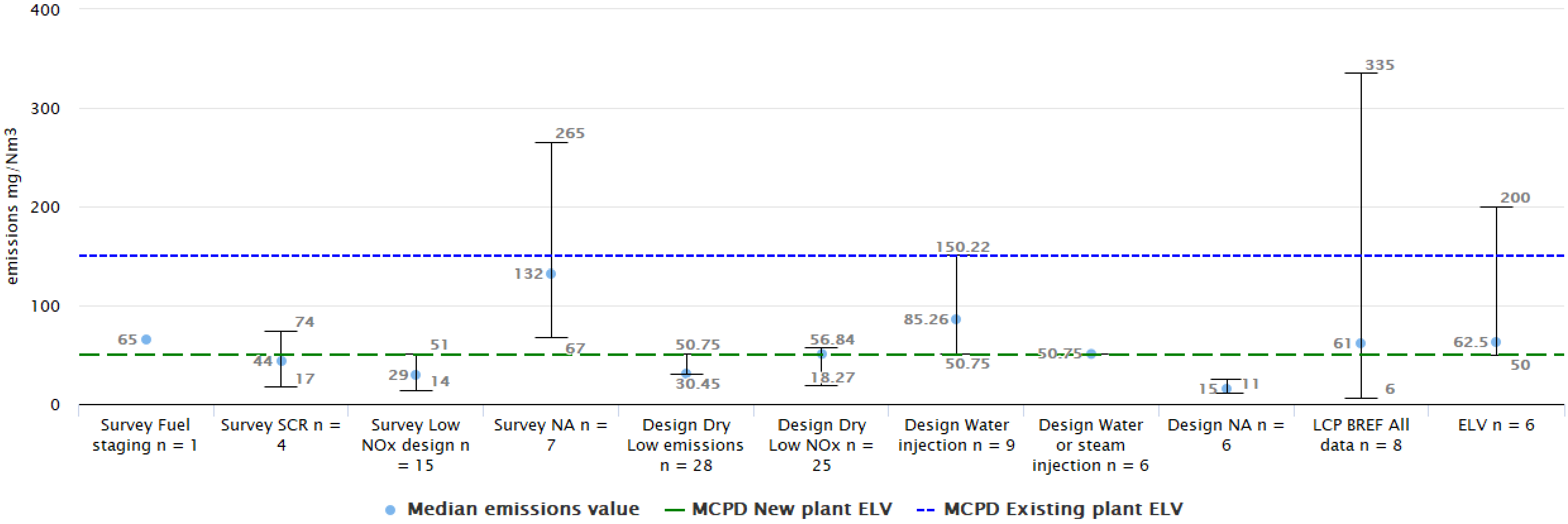
Dust and SO_2 emissions are not considered relevant for natural gas engines, and in line with this knowledge the data contains no ELVs or plants with relevant abatement technologies for these pollutants.

3.2.6.3 Natural gas turbines

NOx emissions

Figure 3-57 shows the results of the comparison of data sources of NO_x emissions for natural gas turbine plants. Compared to natural gas engines, the ELVs vary less, from 50 to 200 mg/Nm³. The MCPD ELV is 50 mg/Nm³ for new plants, and 150 mg/Nm³ for existing plants. As shown in Table 3-2 the minimum limit value is 50 mg/Nm³ from the Netherlands. This is equal to the MCPD, but only for new plants, while the Netherlands applies this to all plants. From the survey data, there is a very stark difference between the plants that apply an abatement technology and those which do not, and those that apply a low NO_x design or other primary technologies can meet or get close to the most stringent limit value.

Figure 3-57 Comparison of median, minimum and maximum values of various sources for NO_x emissions from natural gas turbines



While no performance data from literature was obtained on NO_x emissions, a large sample of design data was available for Gas Turbines, though the abatement technologies in this dataset have more generic names and are not directly comparable to the survey data[14]. Figure 3-57 distinguishes between Dry Low emissions, Dry Low NO_x, Water Injection and/or Steam Injection technology. The turbines listed as 'Dry Low emissions' (DLE) and 'Dry Low NO_x' (DLN) and which are listed with both water and steam injection (WI or SI) are all designed with the most stringent MCPD/NL ELV in mind. The values and ranges are very similar to the survey data. In general, many plants with various different abatement technologies can meet the 50 mg/Nm^3 ELV.

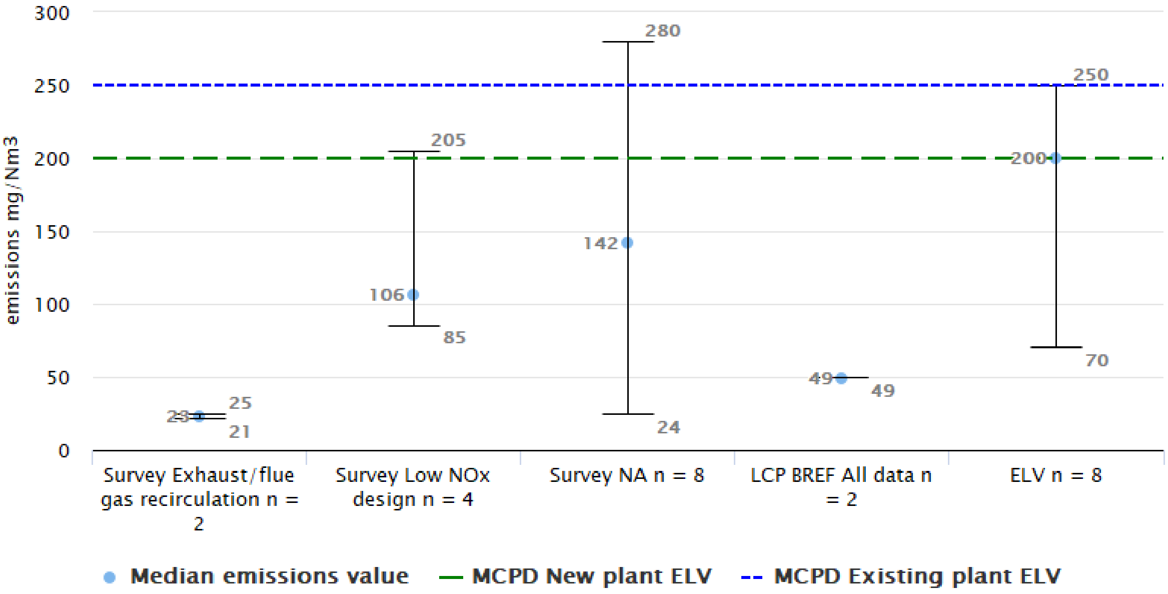
Dust and SO_2 emissions

Dust and SO_2 emissions are not considered material for natural gas turbines, and in line with this knowledge the data contains no ELVs or plants with relevant abatement technologies for these pollutants.

3.2.7 Performance of plants using other gaseous fuels vs references

Figure 3-58 shows the results of the comparison of data sources of NOx emissions for other gaseous fuel boiler plants. It should be noted that ELVs can be very specific for this fuel category, depending on the fuel used. For example, coke oven gas and blast furnace gas have their own unique ELV, which is different from the generic ELVs shown in the figure. However, as this analysis is a general comparison of a larger sample of data, these exceptions are not shown. Plants using flue gas recirculation in the survey deliver the lowest emission levels.

Figure 3-58 Comparison of median, minimum and maximum values of various sources for NOx emissions from other gaseous fuel boilers

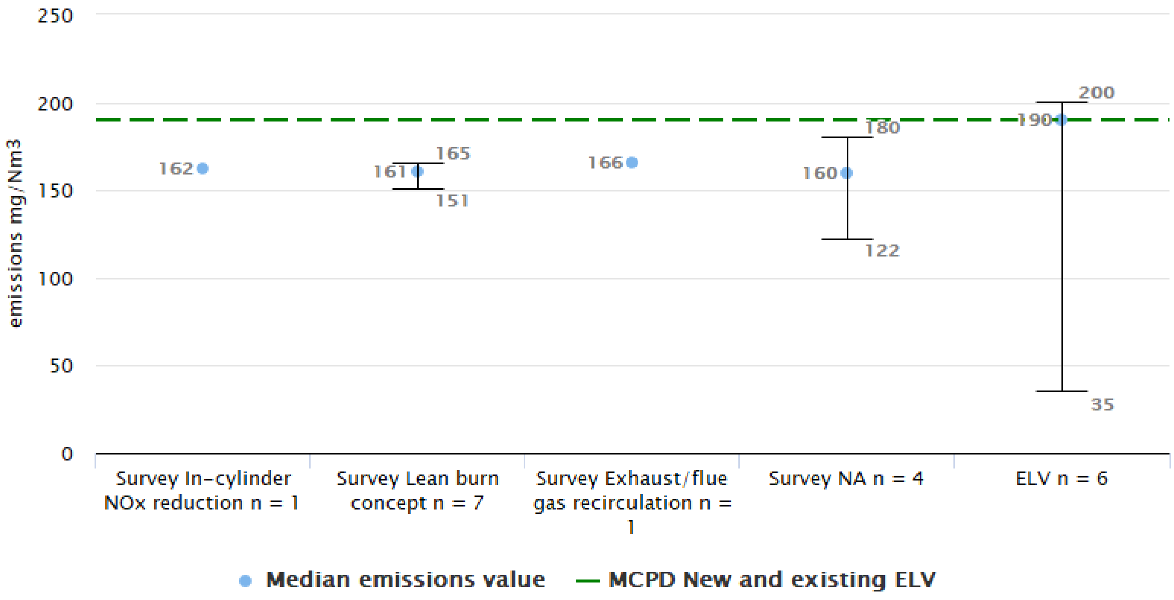


Regarding other gaseous fuel engines, data for reciprocating engines is shown in Figure 3-59. Similar to the boiler sample, due to the heterogeneous nature of this category (with many different emissions for different types of gases), the sample of 5 ELVs includes many exceptions that are not shown on the figure, which apply to specific gases. Only the main MCPD ELV of 190 is shown.

---

[14] SolarTurbines data from various OEM manufacturers (Canada exchange of info new rule gas turbines) available RicardoBox

Figure 3-59 Comparison of median, minimum and maximum values of various sources for NOx emissions from other gaseous fuel engines.



3.3 MCP performance on other emissions to air

The questionnaire that was designed for this project survey on MCP performance allowed plant operators to provide data on other pollutants (beside NOx, SO2, CO or dust). 18 MCPs have reported data on these pollutants that do not have an ELV in the MCPD. These plants operate in Germany, Spain, Italy, Romania or Hungary.

Table 3-3Error! Reference source not found. discloses the summary on emission levels reported for other pollutants. These emission values were reported by boilers and engines.

Table 3-3 Emission level on other pollutants not regulated by MCPD

Castegory	Fuel	Combustion	Size	Count	Average
Formaldehyde	Natural Gas	Reciprocating Engine	<5 MW	3	3.1
	Other gaseous fuel	Reciprocating Engine	<5 MW	8	7.153
	Solid biomass boiler	Boiler	<5 MW	1	<0.1
CH4	Natural Gas	Gas Turbine	20 - 50 MW	4	270
	Natural Gas	Gas Turbine	5 - 20 MW	3	1044
	Natural Gas	Reciprocating Engine	<5 MW	4	368.75
	Natural Gas	Reciprocating Engine	5 - 20 MW	3	397.889
	Other liquid fuel	Reciprocating Engine	20 - 50 MW	1	2.33
	Gas oil	Gas Turbine	20 - 50 MW	1	1.89
TOC	Natural Gas	Reciprocating Engine	20 - 50 MW	1	40.7
	Solid biomass	Boiler	20 - 50 MW	2	35.1
	Solid biomass	Boiler	5 - 20 MW	3	2.9
Hg	Solid biomass	Boiler	20 - 50 MW	1	0.002
Other metals	Solid biomass	Boiler	20 - 50 MW	12	0.012

(1)No information provided on analytical method: most probably NMVOC (PID) calculated at C as full load of engine.

4 Cost of technologies for MCPs

There is a broad array of technologies available to MCPs to reduce the NOx, SOx and dust being emitted from these plants with varying levels of associated costs. The following section reviews costs associated with abatement technologies that reduce NOx, SOx and dust emissions, broken down where available / relevant into Capital Expenditure (CAPEX) and Operational Expenditure (OPEX).

4.1 Summary of technology cost data from literature

This section provides an overview of the cost of emission reduction technologies identified in literature. A complete set of information on these costs is provided in Appendix 4 of this document. The total annualised cost has been obtained as a sum of the OPEX and the annualised CAPEX (CAPEX divided by asset lifetime). Prices have been inflated to year 2018. The values have been updated using the ECB's Harmonized Index of Consumer Prices (based on data from EU28) with cumulative rate of 3.5% and the base case lifetime for all abatement devices was assumed to be 20 years (consistent with literature review lifetime estimates[15] although some devices or plants may have sorter lifetimes). In reality, technology lifetimes can vary considerably between technologies as well as within the same technology depending on operating conditions, maintenance etc. For example, a large diesel engine has an oxygen content of 13-15 vol-% in the flue gas while boilers typically have 3 -6 vol-% O_2. A higher oxygen content means a greater exhaust gas flow and may need a greater abatement system which leads to a higher investment cost.

Emissions can be abated through application of a broad range of abatement technologies. As a result, the costs associated with implementing such technologies varies considerably, particularly across plant size and the fuel used. There is also an important difference between installing the abatement technology as part of a new plant and retrofitting the technology to an existing plant. The information sources do not always provide a full set of basis and assumptions for each cost data. Some sources may even consider the cost of loss of production during construction (production value lost during the shutdown of the plant to build, tie-in and commission the retrofitted assets). Table 4-1 below provides an overview of common technology annualised costs per MW including the wide cost variability. As would be expected, more complex devices (such as SCR, wet Scrubbers or ESP) are more expensive to install than simpler assets. Furthermore, simpler technologies such as bag filters appear to have a much lower variability in the range of the cost e.g. costs per MWth are often lower for larger plants and higher in smaller plants.

Table 4-1 Overview of total annualised cost (OPEX plus annualised CAPEX) for emission reduction technologies (€/MW)

Technology			Average (€/MW)	Max (€/MW)	Min (€/MW)
(Multi) Cyclones	MC	Dust	302	676	97
Bag Filter	BF	Dust	1,107	1,739	580
Electrostatic precipitator	ESP	Dust	2,535	3,478	1,591
Low NOx burner	LNB	NOx	51	60	46
Exhaust gas recirculation	EGR	NOx	191	296	17
Selective catalytic reduction	SCR	NOx	3,730	8,937	121
Selective non-catalytic reduction	SNCR	NOx	1,101	3,845	60
Circulating fluidised bed dry scrubber	CFB	SOx	911	1,528	333
Oxidation Catalyst	OC	CO	5,000		
Wet scrubber	WS	SOx	2,683	12,536	1,066

---

[15] Yang et al., Selection of techniques for reducing shipping NOx and SOx emissions, Transportation Research Part D 17 (2012) 478–486

Technology			Average (€/MW)	Max (€/MW)	Min (€/MW)
Dry scrubber	DS	SOx	756	1,397	241

4.2 Comparison of cost data in questionnaires with literature

4.2.1 Characterisation of cost data provided in survey

4.2.1.1 Overview

This section compares the cost reported in questionnaires by current MCP operators with information found in literature. The information is disaggregated to look at the three main pollutants considered: NOx, SOx and dust. The data provided as part of the information exchange is described before being compared with data in literature.

The cost data provided in questionnaires is summarised below in Table 4-2. The information exchange gathered 25 operating costs and 35 investment costs together with relevant contextual information. Generally speaking, for both CAPEX and OPEX, these data sets contains a high variability. Cost will vary significantly with plant design features (such as gas volume flow rate, existing plant layout, unabated pollutant concentration, etc.) and might also differ from one country to another (e.g. based on different labour costs). The questionnaire provided fields to capture contextual information on whether technology CAPEX referred to a new unit or a plant retrofit. This contextual information was seldom provided so it is likely that costs for new units are aggregated with costs of retrofits. This reduces the accuracy of the cost data provided in the questionnaires since cost for retrofits are normally expected to be higher (around 20-40% higher depending case by case basis).

Table 4-2 Summary of cost data provided in the questionnaires (survey)

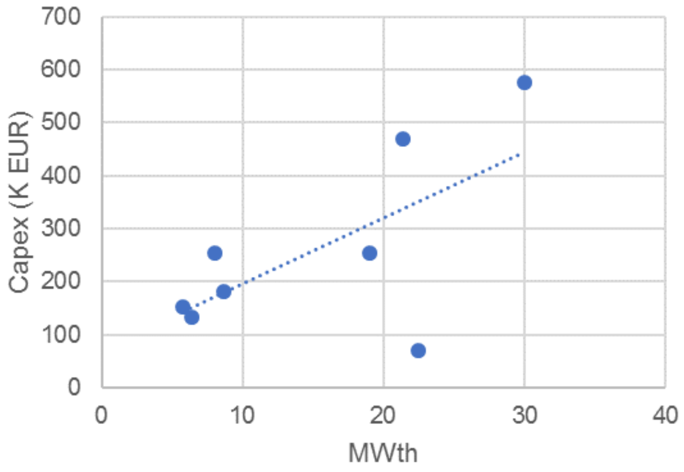
Technology	OPEX data			CAPEX data		
	Sample size	Average (EUR/MW)	Std dev (EUR/MW)	Sample size	Average (EUR/MW)	Std dev (EUR/MW)
NOx						
Flue gas recirculation	3	180	99	3	1,198	1,402
Low NOx burner	0	-	-	7	10,364	11,424
SNCR	3	2,653	1,178	2	20,090	351
SCR	8	1,317	492	8	20,032	29,540
Other	3	168	43	3	10,273	11,424
SOx						
Wet scrubber	2	9,335	10,369	3	68,714	45,864
Dust						
Multicyclone	2	514	601	3	4,399	4,986
Bag Filter	6	763	653	8	19,658	8,561
Dry ESP	2	3,194	1,375	4	27,223	33,997

4.2.1.2 Correlation with plant size (MW_{th})

This analysis was carried out for a limited number of technologies where the sample size was greater than three. The cost data provided does not have a perfect correlation with plant size. Costs are not driven solely by size but a number of other parameters such as plant design e.g. gas volume flowrate. Some of these are shown below.

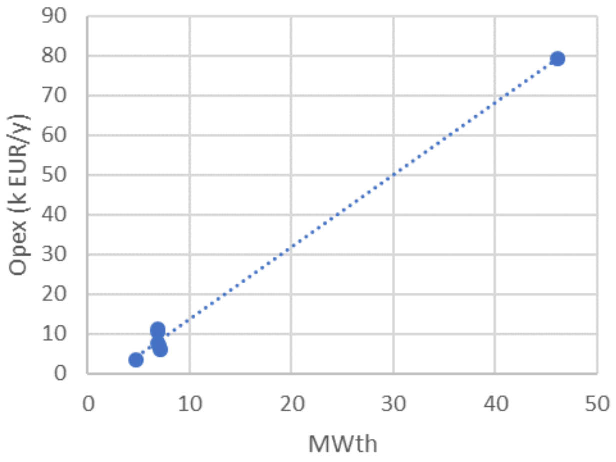
Figure 4-1 shows the relationship of the investment cost with the size of plant for a bag filter. Bar one plant around 20MWth with a low capex cost, the majority of the others show a good correlation between size and cost.

Figure 4-1 Bag filter capex vs plant size (MWth)



This figure below shows the correlation between the operating costs of an SCR with the size of the MCP where it was applied. The correlation is high but biased by the fact that the size (MWth) is unevenly distributed across the range. Data available from the survey, in Figure 4-2, is scarce for larger plant sizes in order to derive clear conclusions.

Figure 4-2 SCR Opex vs plant size (MWth)



4.2.2 Comparing total cost per technology in the questionnaire and the literature

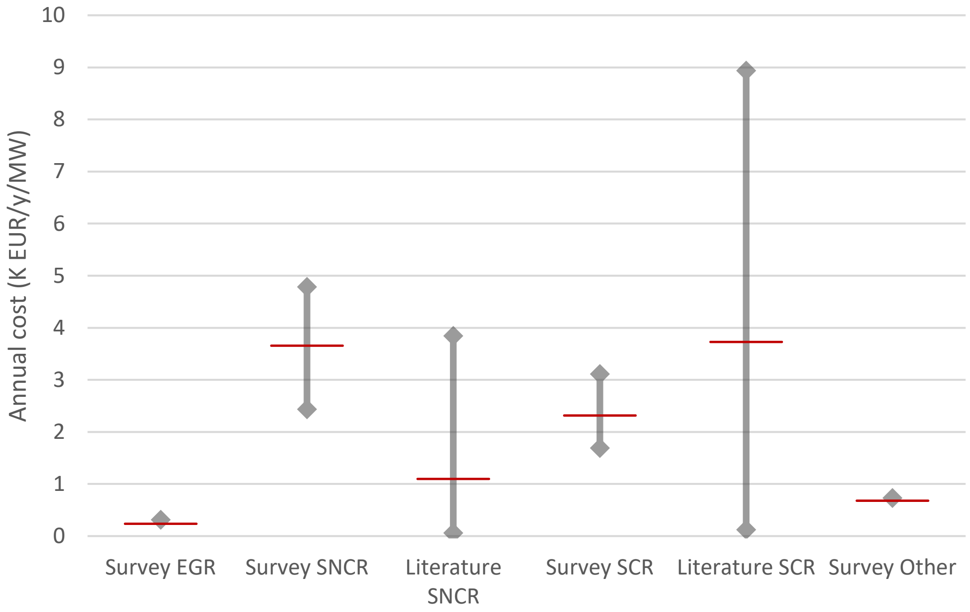
This section compares the costs reported in the survey (questionnaires), for various technologies used to abate NOx, SOx and dust emissions with reference data from literature. The figures show sound data available from both literature and survey however the comparisons are only possible when both the literature and survey data were available in literature.

All costs are presented relative to plant capacity for comparison. However, it should be noted that technology **costs can vary between plants depending on the specific characteristics of the plant** as well as the details of the technologies to be installed: e.g. unabated pollutant concentration, flue gas flowrates, temperature, etc.

4.2.2.1 Costs of reducing NOx

SCR presents the largest variability. Data from the survey for SCR falls inside the cost ranges from literature. These costs are shown in Figure 4-3.

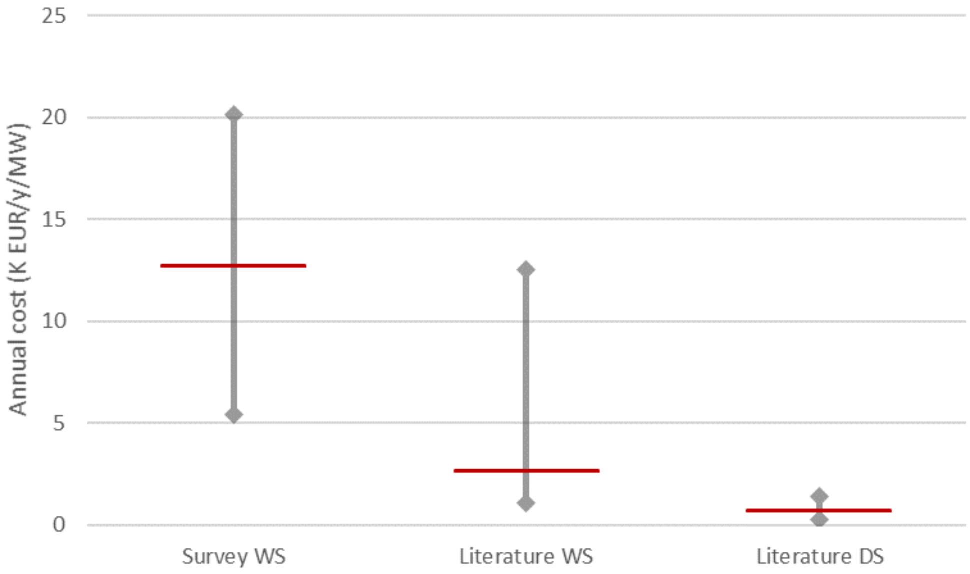
Figure 4-3 Cost for NOx emission reduction in survey and literature



4.2.2.2 Costs of reducing SOx

Regarding SOx emission reduction technologies, the survey gathered costs information for scrubbers only (WS). These costs from the survey are higher than cost data found in literature sources. These costs are shown in Figure 4-4.

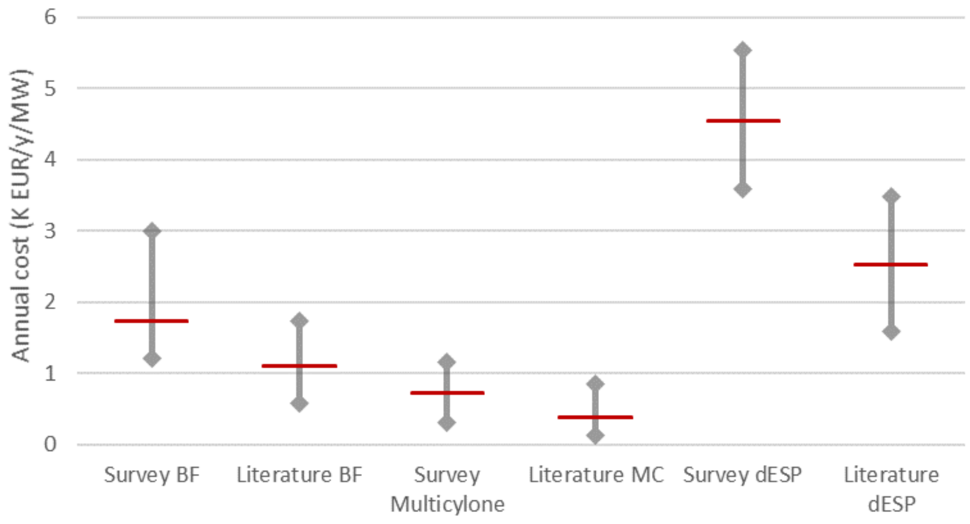
Figure 4-4 Cost for SOx emission reduction in survey and literature



4.2.2.3 Costs of reducing dust

ESP and bag filters show larger costs than cyclones for dust removal. Data from the survey on dry ESPs is higher than cost captured from literature. Multicyclone is the cheapest technology for dust emission reduction based on the data performing. These costs are shown in Figure 4-5.

Figure 4-5 Cost for dust emission reduction in survey and literature



4.2.2.4 Gaps and cost variations

Some technologies were not mentioned in the questionnaires (e.g. use of cleaner fuels). Furthermore, for a number of technologies there are only one or two cost data points. In general, the information provided shows significant variation in the costs reported by current MCP users. Potential (although by no means exclusive) explanatory factors for this may be:

1. The cost data found in the literature review does not account for how the price of technology may change over time. Prices were reported across a range of 20 years, and while the information has been updated to reflect inflation, the costs may have changed further due to broader political/social and economic changes.
2. Secondly, when comparing cost data, comparisons have been conducted by comparing plants that shared the most similar characteristics, e.g. size and fuel burned, however it was not always possible to conduct an exact comparison.
3. The analysis does not look at the country in which the plant is located, this may affect the price paid for procuring, installing and maintaining the technology.
4. There is no precise information on whether costs correspond to retrofit or new build.

4.2.2.5 Environmental benefits vary with emission reduction loads

The benefits generated by an emission abatement device (such as a fabric filter) can be estimated based on the potential reductions in dust emissions for illustrative plants. These emission reductions (tonnes per year) are multiplied by damage cost functions[16] (€ per tonne) to estimate a monetary benefit per year.

Figure 4-6 provides an overview on how these benefits, for a hypothetical illustrative example, would decrease with lower plant loads and with lower unabated emission values:

a) **Loads:** for a given plant type and plant size, these benefits are going to decrease with the average load (plant rate) per year. When a given plant operates at low loads (e.g. 30%) the

---

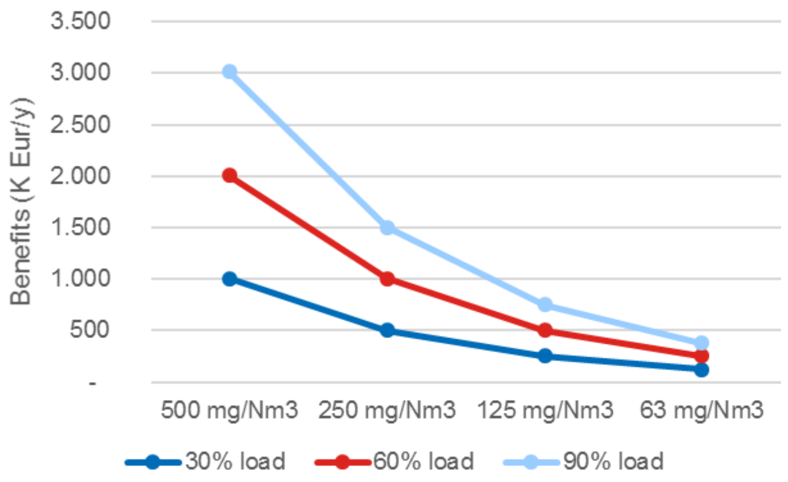
[16] EEA 2014; http://www.externe.info/

final dust abated will be much lower and this will reduce the benefits generated by a given investment. The equipment will be used below its design rates.

b) **Unabated emission levels**: another key parameter to determine the benefits of an emission reduction equipment is the unabated emission value. Assuming emission abatement efficiencies are constant for each technology, the higher the unabated emission levels, the higher the emission reduction will be. These means that a given device will be less cost-effective when the unabated emission levels are lower.

Figure 4-6 is based on application of a fabric filter with a 95% abatement efficiency. This case study is developed for a 12.5 MW_{th} boiler with different unabated emission levels and different plant loads.

Figure 4-6 Benefits decrease with plant loads and/or emission values



There are a number of MCPs that operate at low annual average plant loads across Europe. For example, there are some plants that are only operating as an emergency power supply when there is a supply issue. Some other MCPs are operating only to cover peak power demand. The case study described above shows how the cost effectiveness of emission abatement devices is lower for plants operating a low number of hours and/or have low unabated emission levels.

5 Best available technologies to reduce the environmental impact of MCPs

5.1 Introduction

Building on the findings presented in the previous sections (analysis of questionnaires and additional literature sources), the following sections below present a set of best available technologies for each environmental issue. These are the technologies, primary or secondary, that can be applied to achieve the optimal environmental performance ranges (OPER) and energy efficiency ranges (EER) in MCPs (see Section 2.1 for technology performance criteria and Section 3.1 for the OPERs and EERs identified for each plant category).

For each environmental issue the section contains:

- Summary of their applicability restrictions and performance; and
- Proposal on best available technologies to achieve optimal performance per plant category: The proposal of best technologies for each plant category is presented in a table format. This table contains information on technology applicability limitations. Each table also contains the information gathered in the information exchange. The following legend (Table 5-1) is useful for reading tables.

Table 5-1 Legend for best available technologies selection

Code	Description
Q	Evidence from questionnaires (survey) to support that this technology delivers OPER for this plant category
L	Evidence from literature (performance) to support that this technology delivers OPER for this plant category.
🟧	This technology is applicable for that given type of plant (but NO evidence found proving that delivers OPER)
N.A.	This technology is NOT applicable for that given type of plant
A.R	This technology has certain applicability restrictions for that given type of plant

The following points should be kept in mind when reviewing each of the following sections:

- Primary technologies: In some plant categories the combustion unit plant design may be able to meet ELVs without the use of abatement technologies
- No ELV requirement: there are a number of plant categories with no MCPD ELV for SOx or dust (e.g. dust or SOx for natural gas boilers). These plant categories with no ELVs were taken out of the tables.
- Plant size: Note that some of the more costly and complex, but more effective abatement technologies (such as SCR or WS) may not be viable for smaller combustion plants.
- Plant categories: This report has generated a limited set of plant categories. When summarising applicability restrictions and/or selecting best technologies, some subtle differences may be difficult to capture in a limited set of categories. For example, there are many types of engines and some (e.g. diesel engines) may have better performance whereas others (e.g. stoichiometric rich burn gas engine) may require more effort with respect to abatement.

5.2 Technologies to reduce NO$_x$ emissions

Some primary technologies such as air or fuel staging are generally applicable but others (e.g. low NOx burners) may not always be applicable. Regarding secondary abatement technologies, some may be difficult to retrofit in existing combustion units due to the space availability in the plant lay-out. Space requirements differ significantly from one technology to another (see Table 5-2 for liquid fuel engines).

Table 5-2 Emission reduction space requirements for NOx in engines (Transportation research, 2012)

Technology	Approach	Extra space requirement (m^2): surface lay out needs (50 MWth).
Water/steam addition	Direct water injection	7
	Water fuel emulsion	6
	Humid Air Motor	8
Engine Tuning (Miller)	Internal Engine Modification	0
SCR	SCR	30

Engines have a wide range of specific technologies to reduce NO_x and there have been recent developments in a number of engine specific technologies. Exhaust gas recirculation (EGR) is applicable to four stroke engines[17] (higher rpms) and the lean burn concept is only applicable to gas engines (spark ignition). Selection of engine design has a large impact on emissions e.g. new dual fuel two stroke engines have around 85% lower NO_X, 2 g/KWh[18] (and significantly lower PM and SOx emissions) than diesel engines[19].

Table 5-3 displays the applicability restrictions for NOx reducing technologies. It also provides an overview of total cost (annualised investment plus operating cost) versus abatement efficiencies for each NOx emission reduction technologies. The abatement efficiencies may vary on a case by case basis depending on a number of factors. The majority of technologies are applicable to boilers or turbines.

.

---

[17] https://www.researchgate.net/publication/266672529_Experimental_Analysis_of_Exhaust_Gas_Recirculation_on_DI_Diesel_Engine_Operating_with_Biodiesel

[18] https://www.sintef.no/globalassets/upload/marintek/cimac2014/6---2-s-df-technology-cimac-norway-jan-22-2014.pdf

[19] http://www.ashrae.gr/GrT2016/GrT2016_Yfantis.pdf

Table 5-3 Applicability restrictions, cost and efficiencies for NOx reduction technologies

Technology		Total cost (1)	Abatement efficiency (%) (2)	Applicability		
				Type of plant	Fuel	Other
Dry low NOx burner	(DLN)	Low	Up to 90	Gas turbines	Gaseous	Retrofit: if a burner model is available on market
Air staging	(AS)	Low	40	Boilers		
Low-NOx burners	(LNB)	Low	50	Boilers		
Low-NOx combustion concept in diesel engines	(ET)	Low	40	Engines		Retrofit: if a retrofit package (solution) is available on market
Use of clean fuels (fuel choice)	(FC)		variable		Within the constraints associated with the availability of different types of fuel. For existing combustion plants, the type of fuel chosen may be limited by the configuration and the design of the plant	
Flue-gas or exhaust-gas recirculation	(EGR)	Medium	40-70	Boilers and gas turbines. Applicable to 2 stroke and high speed engines[20]		
Lean-burn concept and advanced lean-burn concept	(LB)		40	New gas engines. Advanced: Not available for gas fired Dual Fuel type engines		
Water steam addition	(WSA)	Medium	60			Retrofit: if a retrofit package (solution) is available on market
Fuel staging	(FS)	Medium	55	Boilers (and limited use in engines[21])		
Selective non-catalytic reduction	(SNCR)	Medium	30-50	Boilers and rich burn or lambda 1 engines		Applicability limited by the required temperature window and residence time for the reactants. Limited in the case of boilers with a high cross-sectional area, plants operated < 1 500 h/yr with highly variable boiler loads.

---

[20] https://www.sciencedirect.com/topics/engineering/exhaust-gas-recirculation

[21] See data from questionnaires in appendix 2

Reduction of the combustion air temperature	(RAT)	Medium	25	Boiler and gas turbines		
Selective catalytic reduction	(SCR)	High	70-90	Gas turbines, engines and boilers		Not generally applicable to combustion plants < 10 MWth (3) or combustion plants operated < 1 500 h/yr (see section 4.2.2.5)

Note: *(1)* Based on the data reported in Section 4 of this document; *(2)* Indicative Value from LCP BREF; (3) See section 3.1.8.6 and Appendix 1 for examples of plants <10 MW using SCR. US EPA SCR factsheet recommending use for larger plants[22].

---

[22] https://www3.epa.gov/ttncatc1/dir1/fscr.pdf

A large number of questionnaires did not report the use of secondary technologies to reduce emissions to air of NOx. These plants have thus provided unabated emission values, or capabilities as a result of primary technologies. This report considers NOx emission data from literature as a secondary source to assess the capabilities of MCPs.

Taking into account the different technology features, their applicability restrictions and costs, Table 5-4 provides proposals for best available technologies for NO_x emission reduction in each plant category covered by the information exchange. The table also reproduces some of the applicability restrictions shown above. In this table, cells in orange colour and no 'Q' nor 'L' indicate that no evidence has been identified for applicability limitations nor for delivering best performance (achieving OPER).

Table 5-4 Best available technology for NO_x emission reduction in MCPs (legend below)

Fuel	Type	(AS)	(FS)	(DLN)	(LNB)	(FC)	(EGR)	(ET)	(LB)	(WSA)	(RAT)	(SNCR)	(SCR)
Solid Biomass	Boiler	Q	Q	N.A.	Q		Q	N.A.				Q&L	
Other solid	Boiler			N.A.			Q	N.A.				L	L
Gas oil	Boiler			N.A.				N.A.				L	L
	Engine	N.A.	N.A.	N.A.	N.A.		A.R.		A.R.		N.A.		L
	G. T.	N.A.	N.A.		N.A.			N.A.				N.A.	
Other liquid	Boiler			N.A.	N.A.			N.A.				L	L
	Engine	N.A.	N.A.	N.A.	N.A.	Q	A.R.		A.R.		N.A.	A.R.	L
Multi-fuel	Boiler			N.A.	Q			N.A.					
Natural Gas	Boiler	Q		N.A.	Q&L		Q	N.A.				L	L
	Engine	N.A.	Q	N.A.	N.A.				Q	A.R.	N.A.	A.R.	Q&L
	G. T.	N.A.	N.A.	Q&L	N.A.			N.A.		L		N.A.	Q
Other gaseous	Boiler			N.A.	L		Q	N.A.				L	L
	Engine	N.A.	N.A.	N.A.	N.A.				Q	A.R.	N.A.		

Legend: Green cells=applicable and evidence based; Orange cells=Potentially applicable but no evidence identified; Black Cells=Not Applicable; Yellow cells= Applicability restrictions

5.3 Technologies to reduce SOx emissions

Some technologies (e.g. boiler sorbent injection) are not applicable to gas turbines or engines. Regarding secondary technologies (abatement devices), some may be difficult to retrofit in existing combustion units due to the space availability in the plant lay-out. Engines have a smaller set of technologies to reduce SOx compared to boilers and gas turbines. Table 5-5 provides an overview of the technologies limitations and associated total cost (annualised investment plus operating cost) versus abatement efficiencies. The abatement efficiencies may vary on a case by case basis depending on a number of factors.

Table 5-5 Applicability restrictions, costs and efficiencies for SOx reduction technologies

Technology		Total cost (1)	Abatement efficiency	Applicability		
				Type of plant	Fuel	Other
Boiler sorbent injection (in-furnace or in-bed)	(BSI)	Medium	60	CFB boilers. Not applicable to grate-fired, BFB boilers		
semi dry scrubber	(CFB)	High	95	Boiler / gas turbines		
Duct sorbent injection	(DSI)	Medium	65	Boilers and gas turbines		
Use of clean fuels (fuel choice)	(FC)	Medium	Variable		Within the constraints associated with the availability of different types of fuel. For existing combustion plants, the type of fuel chosen may be limited by the configuration and the design of the plant	
Treatment of fuels	(TF)	Medium	Variable		Liquid and gaseous fuels	
Flue-gas condenser	(GC)	Medium	60-80	CHP boilers	Solid fuels and multi-fuels	Generally applicable to CHP units provided there is enough demand for low-temperature heat.
Seawater scrubber	(SWS)	High	90	Boiler / gas turbines		Upon availability of seawater. Not generally applicable to combustion plants < 10 MWth or combustion plants operated < 1 500 h/yr.
Spray dry absorber	(SDA)	High	90			
Wet scrubbers	(WS)	High	94			Not generally applicable to combustion plants < 10 MWth or combustion plants operated < 1500 h/yr.

Note: (1) Based on the data reported in Section 4.2 of this document

Taking into account the different technology selection features, their applicability restrictions and costs, this next table provides best available technologies for SO_x emission reduction in each plant category covered by the information exchange. Table 5-6 reproduces applicability restrictions shown above. MCPs using natural gas or gas oil do not have SOx ELVs in the directive and are thus not included in this table. In this table, cells in orange colour and no 'Q' nor 'L' indicate that no evidence has been identified for applicability limitations nor for delivering best performance (achieving OPER).

Table 5-6 Best available technology for SOx emission reduction in MCPs

Fuel	Type	(BSI)	(CFB)	(DSI)	(FC)	(GC)	(TF)	(SWS)	(SDA)	(WS)
Solid Biomass	Boiler	A.R.	🟧	🟧	Q	🟧	N.A.	🟧	🟧	Q
Other solid	Boiler	A.R.	🟧	🟧	🟧	🟧		🟧	🟧	🟧
Other liquid	Boiler	🟧	🟧	🟧	🟧	N.A.	🟧	🟧	🟧	🟧
	Engine	N.A.			Q	N.A.	🟧	N.A.	N.A.	🟧
Multi-fuel	Boiler	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Other gaseous	Boiler	🟧	🟧	🟧	🟧	N.A.	🟧	🟧	🟧	🟧
	Engine	N.A.			🟧	N.A.	Q	N.A.	N.A.	🟧

<u>Legend</u>: Green cells=applicable and evidence based; Orange cells=Potentially applicable but no evidence identified; Black Cells=Not Applicable; Yellow cells= Applicability restrictions

5.4 Technologies to reduce dust emissions

Some technologies such as bag filters or ESPs are generally applicable but other technologies (e.g. multicyclones) are not applicable to gas turbines nor engines. Flue gas desulphurisation technologies (scrubbers) can reduce both SOx and dust emission. Large secondary technologies (abatement devices), may be difficult to retrofit in existing combustion units due to the space availability in the plant lay-out.

Table 5-7 below provides an overview of these limitations. It also provides an overview of total cost (annualised investment plus operating cost) versus abatement efficiencies for each dust emission reduction technologies. The abatement efficiencies may vary in a case by case basis depending on numerous factors.

Table 5-7 Applicability restrictions, efficiencies and cost for dust reduction technologies

Technology		**Total cost** *(1)*	**Abatement efficiency (%)** *(2)*	**Applicability**	
				Type of plant	**Other**
Bag filter	(BF)	High	99	Gas turbines, engines and boilers	
Multicyclones	(MC)	Medium	65	Boilers	
Wet scrubber	(WS)	High	99	Gas turbines, and boilers	Not generally applicable to combustion plants < 10 MWth or combustion plants operated < 1 500 h/yr.
Soot filter	(SF)	Medium	99	Small engines (< 10 MWth)	
Flue-gas condenser	(GC)	Medium	80-90[23]	Solid fuels and multi-fuels boilers	Generally applicable to CHP units provided there is enough demand for low-temperature heat.

---

[23] https://www.infomil.nl/publish/pages/116596/fact_sheets_on_air_emission_abatement_techniques_-_final_2009_02_20.pdf

Technology		**Total cost** (1)	**Abatement efficiency (%)** (2)	**Applicability**	
				Type of plant	**Other**
Electrostatic precipitator	(ESP)	High	98	Gas engines, turbines and boilers	Not generally applicable to combustion plants < 5 MWth$^{(3)}$ or operating < 1500 h/yr.

Note: *(1)* Based on the data reported in section 4.2 of this document; *(2)* LCP BREF; *(3)* Evidence in survey (#470,#486 and #439) that some apply ESP below 10 MWth.

Taking into account the different technology selection features, their applicability restrictions and costs, this next table provides a best available technology for dust emission reduction in each plant category covered by the information exchange. The table also reproduces some of the applicability restrictions shown above. MCPs using natural gas or gas oil do not have dust ELVs in the directive and are thus not included in this table. In this table, cells in orange colour and no 'Q' nor 'L' indicate that no evidence has been identified for applicability limitations nor for delivering best performance (achieving OPER).

Table 5-8 Best available technology for dust emission reduction in MCPs

Fuel	Type	(BF)	(MC)	(WS)	(GC)	(SF)	(ESP)
Solid Biomass	Boiler	Q&L	Q	Q	🟧	N.A.	Q&L
Other solid	Boiler	Q&L	Q	🟧	🟧	N.A.	🟧
Other liquid	Boiler	🟧	🟧	🟧	N.A.	N.A.	🟧
	Engine	🟧	N.A.		N.A.	🟧	🟧
Multi-fuel	Boiler	🟧	🟧	🟧	🟧	N.A.	Q
Other gaseous	Boiler	🟧	🟧	🟧	N.A.	N.A.	🟧
	Engine	🟧	N.A.		N.A.	🟧	🟧

Legend: Green cells=applicable and evidence based; Orange cells=Potentially applicable but no evidence identified; Black Cells=Not Applicable; Yellow cells= Applicability restrictions

5.5 Technologies to reduce CO emissions

In general, technologies to improve the overall environmental performance of combustion plants will reduce CO emissions and unburnt hydrocarbons (see following Section 5.6). Technologies to reduce CO emissions will have some interdependency with those to reduce NOx emissions. In a number of MCP plant categories there are generally trade-offs between low CO, low NOx emissions and high efficiency. These were described in a number of literature sources[24] but was not backed up by data reported via the questionnaires during the information exchange. There are three main approaches to these trade-offs that may come into play, depending on regulatory requirements and economics:

- One approach is to control for lowest NOx accepting a fuel efficiency penalty and possibly higher CO and hydrocarbon emissions.
- A second option is finding an optimal balance between emissions and efficiency.
- A third option is to design for highest efficiency and use post-combustion exhaust treatment to control emissions if required for permitting purposes.

The best available technologies to reduce emissions of CO from MCPs are described in Table 5-9 below. Their cost and efficiency values will vary on a case by case basis and would also depend on the NOx control strategy. Since most of these technologies are applied in combinations with others, it is complex to assign them a precise efficiency range.

---

[24] https://www.nrel.gov/docs/fy04osti/34783.pdf

Table 5-9 Best available technologies for CO reduction technologies in MCPs

Technology		Abatement efficiency (%) *(1)*	Applicability restrictions
Air staging	(AS)	Variable	Boilers
Fuel staging	(FS)	Variable	
Oxidation catalysts	(OC)	Up to 90%	Engines and turbines. Not suitable for small chain Hydrocarbons. The applicability may be limited by the sulphur content of the fuel. The maximum flue-gas temperature is limited to about 560 °C.
Combustion optimisation	(CO)	Variable	Generally applicable.

Note: *(1)* LCP BREF

5.6 Technologies to maximise energy efficiency

The most relevant approaches to increase overall efficiency from large combustion plants, such as combined heat and power or combined cycle are also applicable to MCPs[25]. As described in the previous section, there are some interdependencies between CO, NOx emissions and energy efficiencies. In most combustion plants, maximising energy efficiency would reduce CO emissions but may have a penalty on NOx emissions; this was evident from a number of literature sources[26]. Some technologies are generally applicable (combustion optimisation). Using a combined cycle is subject to heat demand and heat use. Since most of these technologies are applied in combinations with others, it is complex to assign them a precise efficiency range.

The best available technologies to increase efficiencies in MCPs are described in Table 5-10 below. Their cost and efficiency values will vary on a case by case basis and could also depend on the NOx control strategy.

Table 5-10 Best available technologies to increase energy efficiency

Technology		Applicability restrictions
Advanced control system	(ACS)	The applicability to old combustion plants may be constrained by the need to retrofit the combustion system and/or control command system.
Combustion optimisation (Optimisation of burning)	(CO)	Generally applicable.
Fuel blending and mixing (Use of fuels of homogeneous and constant quality)	(FB)	
Dry bottom ash handling	(DBA)	Solid fuel boilers
(Boiler) Combustion unit design and size	(CDS)	Generally applicable to new combustion boilers. Applicable for new installations, lowering fire load.
Combined heat and power	(CHP)	Only applicable to new units where there is a realistic potential for the future use of heat in the vicinity of the unit.
Combined cycle	(CC)	Not economically viable for units with low average yearly loads such as emergency back-up. Applicable to existing units within the

---

[25] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/345189/Part_2_CHP_Technology.pdf

[26] https://www.nrel.gov/docs/fy04osti/34783.pdf

Technology		Applicability restrictions
		constraints associated with the steam cycle design and the space availability.
Flue-gas condenser	(GC)	Generally applicable to CHP boilers provided there is enough demand for low-temperature heat.
Supercritical steam conditions	(SCS)	Boilers. Not applicable when the purpose of the unit is to produce low steam temperatures and/or pressures in process industries. Not applicable to gas turbines and engines generating steam in CHP mode. For units combusting biomass, the applicability may be constrained by high-temperature corrosion in the case of certain biomasses.
Wet stack	(WST)	Generally applicable to new and existing units fitted with wet scrubbers.

Note: *(1)* Based on the data reported in Section 4.2 of this document

Appendices

Appendix 1	Complete emissions questionnaire data analysis (HTML)
Appendix 2	Complete energy efficiency questionnaire data analysis (HTML)
Appendix 3	Complete technology descriptions
Appendix 4	Technology costs
Appendix 5	Engine types
Appendix 6	References

Appendix 1 & 2 – Complete questionnaire data analysis

Emission data Analysis

MCP_InfoExchange_Appendix1_Emissions.h

Energy efficiency data analysis

MCP_InfoExchange_Appendix2_EnergyEffici

Appendix 3 – Complete technology descriptions

Generic technologies for MCPs

Technology name	Advanced control system (ACS)
Description	The use of a computer-based automatic system to control the combustion efficiency and support the prevention and/or reduction of emissions. This also includes the use of high-performance monitoring.
Applicability restrictions	The applicability to old combustion plants may be constrained by the need to retrofit the combustion system and/or control command system
Reference documents	Large Combustion Plant (LCP) BREF.

Technology name	Combustion optimisation (Optimisation of burning -CO)
Description	Technologies taken to maximise the efficiency of energy conversion, e.g. in the furnace/boiler, while minimising emissions (in particular of CO). This is achieved by a combination of techniques including good design of the combustion equipment, optimisation of the temperature (e.g. efficient mixing of the fuel and combustion air) and residence time in the combustion zone and use of an advanced control system.
Applicability restrictions	Generally applicable.
Reference documents	LCP BREF.

Technology name	Use of clean fuels (fuel choice-FC)
Description	Choosing fuels with low Sulphur, Nitrogen and ash content.
Applicability restrictions	Applicable within the constraints associated with the availability of suitable types of fuel with a better environmental profile as a whole, which may be impacted by the energy policy of the Member State, or by the integrated site's fuel balance in the case of combustion of industrial process fuels. Within the constraints associated with the availability of different types of fuel. For existing combustion plants, the type of fuel chosen may be limited by the configuration and the design of the plant
Reference documents	LCP BREF.

Technology name	Treatment of fuels (TF)
Description	Physical, chemical, or biologic treatment of fuels. (e.g. activated carbon for desulphurisation)
Applicability restrictions	Applicable to liquid and gaseous fuels
Reference documents	MCPD work.

Technology name	Fuel blending and mixing (Use of fuels of homogeneous and constant quality)
Description	High quality fuels allow a better tuning of the combustion process. Ensure stable combustion conditions and/or reduce the emission of pollutants by mixing different qualities of the same fuel type.
Applicability restrictions	Generally applicable.
Reference documents	LCP BREF.

Technology name	(Boiler) Combustion unit design and size (CDS)
Description	Good design of furnace, combustion chambers, burners and associated devices.
Applicability restrictions	Generally applicable to new combustion boilers. Applicable for new installations, lowering fire load.
Reference documents	LCP BREF.

Technologies to increase energy efficiency

Technology name	Combined heat and power (CHP)
Description	Cogeneration is the recovery of heat (mainly from the steam system) for producing hot water / steam to be used in industrial processes/activities or in district heating. Additional heat recovery is possible from: the flue-gas; grate cooling; the circulating fluidised bed. The heat from the combustion plant (e.g. turbine, engine) flue-gases may be used for steam production in a heat recovery boiler (also called heat recovery steam generator) or be extracted partially (or sometimes fully) and used for steam supply to consumers, who can then use the steam in their own processes or for other purposes such as district heating or seawater desalination.
Applicability restrictions	Only applicable to new units where there is a realistic potential for the future use of heat in the vicinity of the unit.
Reference documents	LCP BREF.

Technology name	Combined cycle (CC)
Description	Combination of two or more thermodynamic cycles, e.g. a Brayton cycle (gas turbine/combustion engine) with a Rankine cycle (steam turbine/boiler), to convert heat loss from the flue-gas of the first cycle to useful energy by subsequent cycle(s).
Applicability restrictions	Not economically viable for units with low average yearly loads such as emergency back-up. Applicable to existing units within the constraints associated with the steam cycle design and the space availability.
Reference documents	LCP BREF.

Technology name	Flue-gas condenser (GC)
Description	A heat exchanger where water is preheated by the flue-gas before it is heated in the steam condenser. The vapour content in the flue-gas thus condenses as it is cooled by the heating water. The flue-gas condenser is used both to increase the energy efficiency of the combustion unit and to remove pollutants such as dust, SO_X, HCl, and HF from the flue-gas.
Applicability restrictions	Generally applicable to CHP boilers provided there is enough demand for low-temperature heat. Applicable to solid fuels and multi-fuels.
Reference documents	LCP BREF.

Technology name	Supercritical steam conditions (SCS)
Description	The use of a steam circuit, including steam reheating systems, in which steam can reach pressures above 220.6 bar and temperatures of > 540°C.
Applicability restrictions	Not applicable when the purpose of the unit is to produce low steam temperatures and/or pressures in process industries. Not applicable to gas turbines and engines generating steam in CHP mode. For units combusting biomass, the applicability may be constrained by high-temperature corrosion in the case of certain biomasses.
Reference documents	LCP BREF.

Technology name	Wet stack (WST)
Description	The design of the stack in order to enable water vapour condensation from the saturated flue-gas and thus to avoid using a flue-gas reheater after the wet scrubber.
Applicability restrictions	Generally applicable to new and existing units fitted with wet scrubber.
Reference documents	LCP BREF.

Technology name	Dry bottom ash handling
Description	Dry hot bottom ash falls from the furnace onto a mechanical conveyor system and, after redirection to the furnace for reburning, is cooled down by ambient air. Useful energy is recovered from both the ash reburning and ash cooling
Applicability restrictions	Applicable to boilers. There may be technical restrictions that prevent retrofitting to existing combustion units.
Reference documents	LCP BREF.

Technologies to control NOx and/or CO

Technology name	Air staging (AS)
Description	The creation of several combustion zones in the combustion chamber with different oxygen contents for reducing NO_X emissions and ensuring optimised combustion. The technique involves a primary combustion zone with sub-stoichiometric firing (i.e. with deficiency of air) and a second reburn combustion zone (running with excess air) to improve combustion. Some old, small boilers may require a capacity reduction to allow the space for air staging.
Applicability restrictions	Applicable to boilers.
Reference documents	LCP BREF.

Technology name	Dry low-NO_X burners (DLN)
Description	Gas turbine burners that include the premixing of the air and fuel before entering the combustion zone. By mixing air and fuel before combustion, a homogeneous temperature distribution and a lower flame temperature are achieved, resulting in lower NO_X emissions.
Applicability restrictions	Gas turbines: The applicability may be limited in the case of turbines where a retrofit package is not available or when water/steam addition systems are installed.

Reference documents	LCP BREF.

Technology name	Flue-gas or exhaust-gas recirculation (EGR)
Description	Recirculation of part of the flue-gas to the combustion chamber to replace part of the fresh combustion air, with the dual effect of cooling the temperature and limiting the O_2 content for nitrogen oxidation, thus limiting the NO_X generation. It implies the supply of flue-gas from the furnace into the flame to reduce the oxygen content and therefore the temperature of the flame. The use of special burners or other provisions is based on the internal recirculation of combustion gases which cool the root of the flames and reduce the oxygen content in the hottest part of the flames.
Applicability restrictions	Applicable to boilers and gas turbines. Applicable to 2 stroke high speed engines
Reference documents	LCP BREF.

Technology name	Fuel staging (FS)
Description	The technique is based on the reduction of the flame temperature or localised hot spots by the creation of several combustion zones in the combustion chamber with different injection levels of fuel and air. The retrofit may be less efficient in smaller plants than in larger plants.
Applicability restrictions	Applicable to boilers (and limited use in engines).
Reference documents	LCP BREF.

Technology name	Lean-burn concept and advanced lean-burn concept (LB)
Description	The control of the peak flame temperature through lean-burn conditions is the primary combustion approach to limiting NO_X formation in gas engines. Lean combustion decreases the fuel to air ratio in the zones where NO_X is generated so that the peak flame temperature is less than the stoichiometric adiabatic flame temperature, therefore reducing thermal NO_X formation. The optimisation of this concept is called the 'advanced lean-burn concept'.
Applicability restrictions	Applicable to new gas engines. Advanced: Not available for gas fired Dual Fuel type engines.
Reference documents	LCP BREF.

Technology name	Low-NO_X burners (LNB)
Description	The technique (including ultra- or advanced low-NO_X burners) is based on the principles of reducing peak flame temperatures; boiler burners are designed to delay but improve the combustion and increase the heat transfer (increased emissivity of the flame). The air/fuel mixing reduces the availability of oxygen and reduces the peak flame temperature, thus retarding the conversion of fuel-bound nitrogen to NO_X and the formation of thermal NO_X, while maintaining high combustion efficiency. It may be associated with a modified design of the furnace combustion chamber. The design of ultra-low-NO_X burners (ULNBs) includes combustion staging (air/fuel) and firebox gases' recirculation (internal flue-gas recirculation). The performance of the

Technology name	Low-NO_X burners (LNB)
	technique may be influenced by the boiler design when retrofitting old plants.
Applicability restrictions	Applicable to boilers
Reference documents	LCP BREF.

Technology name	Low-NO_X combustion concept in diesel engines (ET-engine tuning)
Description	The technique consists of a combination of internal engine modifications, e.g. combustion and fuel injection optimisation (the very late fuel injection timing in combination with early inlet air valve closing), turbocharging or Miller cycle.
Applicability restrictions	Gas, Diesel and Dual Engine. Retrofit: if retrofit package (solution) is not available in the market.
Reference documents	LCP BREF.

Technology name	Oxidation catalysts (OC)
Description	The use of catalysts (that usually contain precious metals such as palladium or platinum) to oxidise carbon monoxide and unburnt hydrocarbons with oxygen to form CO_2 and water vapour.
Applicability restrictions	The applicability may be limited by the sulphur content of the fuel. The maximum flue-gas temperature is limited to about 560 °C.. Not suitable for abatement of short chain alkanes CH_4, C_2H_6 and C_3H_8.
Reference documents	LCP BREF.

Technology name	Reduction of the combustion air temperature (RAT)
Description	The use of combustion air at ambient temperature. The combustion air is not preheated in a regenerative air preheater. May reduce the efficiency of the combustion unit.
Applicability restrictions	Applicable to gas turbine and boilers
Reference documents	LCP BREF.

Technology name	Selective catalytic reduction (SCR)
Description	Selective reduction of nitrogen oxides with ammonia or urea in the presence of a catalyst. The technique is based on the reduction of NO_X to nitrogen in a catalytic bed by reaction with ammonia (in general aqueous solution) at an optimum operating temperature of around 300–450 °C. Several layers of catalyst may be applied. A higher NO_X reduction is achieved with the use of several catalyst layers. The technique design can be modular, and special catalysts and/or preheating can be used to cope with low loads or with a wide flue-gas temperature window. 'In-duct' or 'slip' SCR is a technique that combines SNCR with downstream SCR which reduces the ammonia slip from the SNCR unit. SCR is widely used for gas turbines.
Applicability restrictions	Not generally applicable to combustion plants < 10 MWth or combustion plants operated < 1 500 h/yr. Retrofitting existing units may be limited due to space constraints
Reference documents	LCP BREF.

Technology name	Selective catalytic reduction (SCR)
	US EPA: SCR fact sheet[27]

Technology name	Selective non-catalytic reduction (SNCR)
Description	Selective reduction of nitrogen oxides with ammonia or urea without a catalyst. The technique is based on the reduction of NO_X to nitrogen by reaction with ammonia or urea at a high temperature. The operating temperature window is maintained between 800 °C and 1 000 °C for optimal reaction. The use of the technique leads to ammonia emissions
Applicability restrictions	Applicable limited by the required temperature window and residence time for the reactants. Limited in the case of boilers with a high cross-sectional area, plants operated < 1 500 h/yr with highly variable boiler loads. Applicable to boilers and small Rich burn or Lambda 1 engines
Reference documents	LCP BREF.

Technology name	Water/steam addition (WSA)
Description	Water or steam is used as a diluent for reducing the combustion temperature in gas turbines, engines or boilers and thus the thermal NO_X formation. It is either premixed with the fuel prior to its combustion (fuel emulsion, humidification or saturation) or directly injected in the combustion chamber (water/steam injection). Fuel consumption might increase with 1 % or more.
Applicability restrictions	Retrofit: if a retrofit package (solution) is available on market.
Reference documents	LCP BREF.

Technologies to control SOx

Technology name	Flue-gas condenser (GC)
Description	A heat exchanger where water is preheated by the flue-gas before it is heated in the steam condenser. The vapour content in the flue-gas thus condenses as it is cooled by the heating water. The flue-gas condenser is used both to increase the energy efficiency of the combustion unit and to remove pollutants such as dust, SO_X, HCl, and HF from the flue-gas.
Applicability restrictions	Generally applicable to CHP boilers provided there is enough demand for low-temperature heat. Applicable to solid fuels and multi-fuels.
Reference documents	LCP BREF.

Technology name	Boiler sorbent injection BSI (in-furnace or in-bed)
Description	The direct injection of a dry sorbent into the combustion chamber, or the addition of magnesium- or calcium-based adsorbents to the bed of a fluidised bed boiler. The surface of the sorbent particles reacts with the SO_2 in the flue-gas or in the fluidised bed boiler. It is mostly used in combination with a dust abatement technique.
Applicability restrictions	Generally applicable to boilers. Not applicable to grate-fired, BFB boilers.

---

[27] https://www3.epa.gov/ttncatc1/dir1/fscr.pdf

Reference documents	LCP BREF.

Technology name	Circulating fluidised bed (CFB) dry scrubber
Description	Flue-gas from the boiler air preheater enters the CFB absorber at the bottom and flows vertically upwards through a Venturi section where a solid sorbent and water are injected separately into the flue-gas stream. It is mostly used in combination with a dust abatement technique.
Applicability restrictions	Applicable to boilers and gas turbines.
Reference documents	LCP BREF.

Technology name	Duct sorbent injection (DSI)
Description	The injection and dispersion of a dry powder sorbent in the flue-gas stream. The sorbent (e.g. sodium carbonate, sodium bicarbonate, hydrated lime) reacts with acid gases (e.g. the gaseous sulphur species and HCl) to form a solid which is removed with dust abatement techniques (bag filter or electrostatic precipitator). DSI is mostly used in combination with a bag filter.
Applicability restrictions	Boilers and gas turbines
Reference documents	LCP BREF.

Technology name	Seawater scrubber (SWS)
Description	A specific non-regenerative type of wet scrubbing using the natural alkalinity of the seawater to absorb the acidic compounds in the flue-gas.
Applicability restrictions	Applicable to boilers and gas turbines. Upon availability of seawater. Not generally applicable to combustion plants < 10 MWth or combustion plants operated < 1 500 h/yr
Reference documents	LCP BREF.

Technology name	Spray dry absorber (SDA)
Description	A suspension/solution of an alkaline reagent is introduced and dispersed in the flue-gas stream. The material reacts with the gaseous sulphur species to form a solid which is removed with dust abatement techniques (bag filter or electrostatic precipitator). SDA is mostly used in combination with a bag filter.
Applicability restrictions	Applicable to boilers and gas turbines
Reference documents	LCP BREF.

Technology name	Wet scrubbing (WS)
Description	Use of a liquid, typically water or an aqueous solution, to capture the acidic compounds from the flue-gas by absorption. Scrubbers methods would produce an end product which is to be disposed/utilized in an environmental acceptable way. End product composition varies a lot between different methods.
Applicability restrictions	Applicable to boilers and gas turbines. Not generally applicable to combustion plants < 10 MWth or combustion plants operated < 1 500 h/yr. Retrofitting existing units may be limited due to space constraints

Reference documents	LCP BREF. US EPA fact sheet[28].

Technologies to control dust

Technology name	Bag filter (BF)
Description	Bag or fabric filters are constructed from porous woven or felted fabric through which gases are passed to remove particles. The use of a bag filter requires the selection of a fabric suitable for the characteristics of the flue-gas and the maximum operating temperature.
Applicability restrictions	Generally applicable.
Reference documents	LCP BREF.

Technology name	Ceramic filter
Description	In a ceramic filter the contaminated gas is led through the filtering material, in a process comparable to that of a fabric filter. The difference with a fabric filter is that the filtering material is ceramic. There are also designs where acidic compounds such as HCl, NO_X, SO_X and dioxins are removed. In such a case, the filtering material is fitted with catalysts and the injection of reagents may be necessary. Selected for high flue gas temperature applications.
Applicability restrictions	Limited applicability on gas streams containing sticky dust.
Reference documents	CWW BREF.

Technology name	Dry or semi-dry scrubber
Description	See general description of each technique (i.e. spray dry absorber (SDA), duct sorbent injection (DSI), circulating fluidised bed (CFB) dry scrubber) in previous section. There are co-benefits in the form of dust and metal emissions reduction.
Applicability restrictions	Applicable to boilers and gas turbines
Reference documents	LCP BREF.

Technology name	Electrostatic precipitator (ESP)
Description	Electrostatic precipitators operate such that particles are charged and separated under the influence of an electrical field. Electrostatic precipitators are capable of operating under a wide range of conditions. The abatement efficiency typically depends on the number of fields, the residence time (size), catalyst properties, and upstream particle removal devices. ESPs generally include between two and five fields. The most modern (high-performance) ESPs have up to seven fields.
Applicability restrictions	Not generally applicable to combustion plants < 5 MWth or combustion plants operated < 1 500 h/yr.
Reference documents	LCP BREF.

Technology name	Multicyclones (MC)

---

[28] https://www3.epa.gov/ttn/catc/dir1/fpack.pdf

Description	Set of dust control systems, based on centrifugal force, whereby particles are separated from the carrier gas, assembled in one or several enclosures.
Applicability restrictions	Applicable to boilers
Reference documents:	LCP BREF.

Technology name	Soot Filters (SF)
Description	A diesel particulate filter removes soot particles from the exhaust gas that are produced during the combustion process that takes place in the engine. This is done by directing the exhaust gas through filter substrate (different materials are used such as ceramic). Soot particles are deposited on the walls of the channels as the exhaust gas passes through the structure. There are different approaches to regenerate these devices.
Applicability restrictions	Small size engines (<10MW)
Reference documents:	US EPA[29]

---

[29] https://www.epa.gov/sites/production/files/2016-03/documents/420f10029.pdf

Appendix 4 – Technology cost data

NOx reduction technologies

Technology	Plant type	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source:
Air Staging (AS)					
	250MW$_{th}$ boiler	€1 million	€2400-8000/ tonne		LCP BREF
Dry low-NOx burner (DLN)					
	140 MW$_{th}$ gas turbine	€14,286–28,571	€500,000		LCP BREF
Flue-gas or exhaust gas recirculation (EGR)					
New *Existing*	20 MW$_{th}$	20 000 50 000			LCP BREF
Combustion modification – assumed EGR	Biomass (boiler)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€387	
	5-20MW$_{th}$			€471	
	20-50MW$_{th}$			€389	
Combustion modification – assumed EGR	Liquid fuels (boiler)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€364	
	5-20MW$_{th}$			€73	
	20-50MW$_{th}$			€26	
	4-stroke engine at 400-1,600 rpm	36-45[30] 10[31] EUR/kw 5-8% of fuel costs			
EGR	Biomass (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€2061-2338	
	5-20MW$_{th}$			€564	
	20-50MW$_{th}$			€335	
EGR	Other solid fuels (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€459	
	5-20MW$_{th}$			€564	
	20-50MW$_{th}$			€335	
Use of clean fuels (fuel choice-FC)					

---

[30] For equipment

[31] For installation

Technology	Plant type	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source:
Fuel switch to natural gas	Other solid fuels (boiler)			€/MW	AMEC 2014
	1-5MW$_{th}$			€35,289	
	5-20MW$_{th}$			€45,034	
	20-50MW$_{th}$			€35,851	
Biomass Cofiring for Coal Plants		€/kw	€/kw-yr		EPA[32]
	5MW	581	29		
	10MW	489	19		
	15MW	441	14		
	20MW	410	11		
	25MW	389	10		
	30MW	371	11		
	35MW	357	11		
	40MW	464	11		
	45MW	335	10		
	50MW	372	9		
Fuel switching – to biomass	Other solid fuels (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€6,523	
	5-20MW$_{th}$			€8,343	
	20-50MW$_{th}$			€6,628	
Fuel switch (natural gas)	Other solid fuels (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€2,338	
	5-20MW$_{th}$			€2,991	
	20-50MW$_{th}$			€2,432	
Fuel staging (FS)					
	250MW$_{th}$ boiler	10,000			
Lean-burn concept and advanced learn-burn concept (LB)					
Lean NOx Catalyst		$23,191,270			EPA p.71[33]
Low-NOx burners (LNB)					
	250 MW$_{th}$ solid fuel burner	€68,005	€400		LCP BREF

---

[32] https://www.epa.gov/sites/production/files/2015-07/documents/chapter_5_emission_control_technologies.pdf

[33] https://www.epa.gov/sites/production/files/2014-02/documents/3_2010_diesel_eng_alternativecontrol.pdf

Technology	Plant type	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source:
Low NOx	Natural gas (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €728 €644 €981	AMEC, 2014
Low NOx	Other gaseous fuels (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €728 €244 €981	AMEC, 2014
Low-NOx combustion concept in diesel engines (engine tuning-ET)					
Internal Engine Modifications: Basic IEM	‘Young Engines’ Small Medium Large ‘Older Engines’ Small Medium Large	€ 675 363 482 3.6 933 482	€/kW 0.57 0.45 0.42 2.94 1.02 0.61		Entec, 2005[34]
Internal Engine Modifications: Advanced IEM	Small Medium Large	€62423 €13960 €4315	€30/kW €10/kW €6/kW		Entec, 2005[35]
Oxidation catalyst (OC)					
Diesel Oxidisation Catalyst		€49179	€9724		EPA p.60[36]
Reduction of combustion air temperature (RAT)					
	60MW$_{th}$ natural gas fired boiler			€63,272	LCP BREF
Selective Catalytic Reduction (SCR)					

---

[34] http://ec.europa.eu/environment/air/pdf/task2_nox.pdf5612

[35] http://ec.europa.eu/environment/air/pdf/task2_nox.pdf

[36] https://www.epa.gov/sites/production/files/2014-02/documents/3_2010_diesel_eng_alternativecontrol.pdf

Technology	Plant type	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source:
SCR+					Ricardo (2017)
New		1094	146		
Existing		-	-		
SCR++					
New		2164	153		
Existing		-	-		
SCR	Biomass and other solid fuels (boiler)			€/MW	AMEC 2014
	1-5MW$_{th}$			€314-14218	
	5-20MW$_{th}$			€402-13440	
	20-50MW$_{th}$			€319-12574	
SCR	Other Solid fuels (boiler)			€/MW	AMEC 2014
	1-5MW$_{th}$			€351-16284	
	5-20MW$_{th}$			€449-14217	
	20-50MW$_{th}$			€357-13191	
SCR	Liquid fuels (boiler)			€/MW	AMEC 2014
	1-5MW$_{th}$			€265-2612	
	5-20MW$_{th}$			€339-11960	
	20-50MW$_{th}$			€269-10468	
SCR	Natural gas and other gaseous fuels (boiler)			€/MW	AMEC 2014
	1-5MW$_{th}$			€238-2939	
	5-20MW$_{th}$			€339-11960	
	20-50MW$_{th}$			€242-10153	
SCR	5-22 MW gas turbine	TCI ($MM)	€/ton NOx removed		Solar Turbines
	Taurus 60	€194,000	52,348		
	Taurus 70	€216,000	47,509		
	Mars 100	€234,000	34,576		
	Titan 130	€279,000	33,520		
	Titan 250	€324,000	30,265		

Technology	Plant type	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source:
SCR (retrofit)	(4stroke) Medium rpm range	67-112 EUR/kW	3.9-4.7 EUR/kW		Danish EPA[37]
SCR	Biomass (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €249-13060 €602-8869 €319-8942	AMEC, 2014
SCR	Liquid fuels (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/ME €265-13060 €339-11960 €269-10468	AMEC, 2014
SCR	Natural gas (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €721-9239 €647-14363 €734-13483	AMEC, 2014
SCR	Other gaseous fuels 'Other technologies' 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €721-9239 €647-14363 €734-13483	AMEC, 2014
SCR	Other solid fuels (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €351-16363 €449-14217 €357-13191	AMEC, 2014
Selective non-catalytic reduction (SNCR)					
SNCR	Biomass (boiler) 1-5MW$_{th}$			€/MW €251-1600	AMEC 2014

---

[37] https://www.danskehavne.dk/wp-content/uploads/2015/11/partnerskab-for-reneres-skibsfart-technical-review-catalogue-of-reduction-technologies.pdf

Technology	Plant type	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source:
	5-20MW$_{th}$			€321-2879	
	20-50MW$_{th}$			€255-5786	
SNCR	Other solid fuels (boiler)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€251-1600	
	5-20MW$_{th}$			€359-2879	
	20-50MW$_{th}$			€285-5786	
SNCR	Liquid fuels (boiler)			€/MW	AMEC 2014
	1-5MW$_{th}$			€198-1600	
	5-20MW$_{th}$			€254-2879	
	20-50MW$_{th}$			€166-5786	
SNCR	Natural gas (boiler)			€/MW	AMEC 2014
	1-5MW$_{th}$			€110-1600	
	5-20MW$_{th}$			€137-2879	
	20-50MW$_{th}$			€150-5786	
SNCR	Other gaseous fuels (boiler)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€142-1600	
	5-20MW$_{th}$			€137-2879	
	20-50MW$_{th}$			€97-5786	
SNCR	Biomass (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€145-1600	
	5-20MW$_{th}$			€148-2879	
	20-50MW$_{th}$			€117-5786	
SNCR	Liquid fuels (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€198-1600	
	5-20MW$_{th}$			€254-2879	
	20-50MW$_{th}$			€166-5786	
SNCR	Natural gas (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€194-1600	
	5-20MW$_{th}$			€295-2879	

Technology	Plant type	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source:
	20-50MW$_{th}$			€363-5786	
SNCR	Other gaseous fuels (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€311-1600	
	5-20MW$_{th}$			€295-2879	
	20-50MW$_{th}$			€293-2876	
SNCR					Ricardo (2017)
New		157,429	926		
Existing		11,485	793		
SNCR	Other solid fuels (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€336-1600	
	5-20MW$_{th}$			€159-2879	
	20-50MW$_{th}$			€285-5786	
Water/steam addition (WSA)					
Retrofit	140 MW$_{th}$ gas turbine	764,000			LCP BREF
Water Injection	Natural gas (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€2061-2339	
	5-20MW$_{th}$			€2061-2339	
	20-50MW$_{th}$			€2061-233	
Primary Technologies					
New	Cost per MWth	6,220	182		Ricardo (2017)
Existing		4,311	126		
Combi primary technologies and SCR					
New	Cost per MWth	54,059	926		Ricardo (2017)
Existing		35,910	793		
Combi primary technologies and SNCR					
New	Cost per MWth	54,059	3,834		Ricardo (2017)
Existing		35910	3,302		
Direct Water Injection (WSA)					
	Small	€54293	€13276/yr		ENTEC, 2005
	Medium	€21646	€8685/yr		
	Large	€15684	€7743/yr		

Technology	Plant type	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source:
Humid Air Motors (WSA)					
	New Build				ENTEC, 2005
	Small	€269276	€1373		
	Medium	€150394	€891		
	Large	€114041	€795		
	Retrofit				ENTEC, 2005
	Small	€269275	€1373		
	Medium	€162031	€891		
	Large	€134820	€795		

SOx reduction technologies

Technology	Plant Size	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source
Boiler sorbent injection (BSI-in furnace or in bed)					
Use of sorbents in fluidised bed combustion systems	1 GW CFB coal-fired boiler	-	€0.25/MW_{th}		LCP BREF p183
Circulating fluidised bed (CFB) dry scrubber					
Liquid Fuels	Dry FGD (boiler)			€/MW	AMEC, 2014
	1-5MW_{th}			€1000-1040	
	5-20MW_{th}			€1279-1330	
	20-50MW_{th}			€1016-1057	
Other Gaseous Fuels	Dry FGD (boiler)			€/MW	AMEC, 2014
	1-5MW_{th}			€460-796	
	5-20MW_{th}			€588634	
	20-50MW_{th}			€529-1540	
Other solid fuels	Dry FGD (boiler)			€/MW	AMEC, 2014
	1-5MW_{th}			€1933-1987	
	5-20MW_{th}			€2040-2109	
	20-50MW_{th}			€1621-1675	
Duct sorbent injection (DSI)					
	1 GW_{th} CFB coal-fired boiler		€0.25/MW_{th}		LCP BREF

Technology	Plant Size	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source
	Boiler, 84% of SO$_2$ is removed	€18,082	$704-1056/t SO$_2$		IEA[38] p38
Use of clean fuels (FC-fuel choice)					
Fuel switch to 0.1% gas oil	Liquid fuels (boiler) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €16,734 €3,347 €1,195	AMEC 2014
Co-fire biomass	Other solid fuels (boiler) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €6,523 €8,343 €6,628	AMEC 2014
Fuel switch to natural gas	Other solid fuels (boiler) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €35,292 €45,034 €35,851	AMEC 2014
Fuel switch to low sulphur coal	Other solid fuels (boiler) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €2,338 €2,991 €2,376	AMEC, 2014
Liquid fuels – fuel switch	‘Other technologies’ 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €16,734 €3,347 €1,195	AMEC, 2014
fuel switch (natural gas)	Other solid fuels (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €35,289 €45,034 €32,452	AMEC, 2014
Seawater scrubber (SWS)					

---

[38] https://www.usea.org/sites/default/files/112012_Low%20water%20FGD%20technologies_ccc210.pdf

Technology	Plant Size	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source
	300-500 MWe	£128/KWe	£0.0021/kWe		LCP BREF
Spray dry absorber (SDA)					
	>200 *<200*	€56.8-212 /kW €212-2128 /kW	€57-142 /kW €14-425 /kW		EPA[1]
Wet scrubber (WS)					
	>400 *<400*	€142-354 /kW €353-2127 /kW	€2.8-11.4/kW €11.4-28 /kW		EPA[39]
New *Existing*		€35-50 kWe €60-300 kWe	€0.4 /kWe €0.7/ kWe		*LCP BREF*
WS	Biomass (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €3762 €4022 €1607	AMEC, 2014
WS	Liquid fuels (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €4350 €5036 €2204	AMEC, 2014
WS	Other gaseous fuels (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €7216 €5401 €2495	AMEC, 2014
WS	Other solid fuels (Other technologies) 1-5MW$_{th}$ 5-20MW$_{th}$ 20-50MW$_{th}$			€/MW €4339 €5912 €2900	AMEC, 2014
Wet Scrubbing					

---

[39] https://www3.epa.gov/ttn/catc/dir1/ffdg.pdf

Technology	Plant Size	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source
WS					Ricardo (2017)
New		73,786	3,512		
Existing		73,786	3,512		
WS+					
New		99,478	4,387		
Existing		73,786	3,512		
WS++					
New		125,172	9,363		
Existing					

Dust reduction technologies

Technology	Plant Size	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source
Bag Filter (BF)					
		€19.6/KWe	€0.0022/kWe		LCP BREF
Bag filter	Liquid fuels (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€927-2843	
	5-20MW$_{th}$			€927-2015	
	20-50MW$_{th}$			€1324-2808	
Bag filter	Other solid fuels (Other technologies)			€/MW	AMEC, 2014
	1-5MW$_{th}$			€1208-2887	
	5-20MW$_{th}$			€1207-2624	
	20-50MW$_{th}$			€1163-2250	
Electrostatic precipitator (ESP)					
ESP					Ricardo (2017)
New		59873	2250		
Existing		59783	2250		
ESP+					
New		86808	3242		
Existing		59873	2250		
ESP++					
New		125860	2923		
Existing		59873	2250		
ESP	Liquid fuels (Other technologies)			€/MW	AMEC, 2014

Technology	Plant Size	Capex (EUR)	Opex (EUR)	Total Annualised Cost (K EUR/y)	Source
	1-50MW$_{th}$			€692-699	
ESP	Natural gas (Other technologies)			€/MW	AMEC, 2014
	1-50MW$_{th}$			€692-699	
Multicyclones (MC)					
		€7787-12172	€2434-29609		EPA[40]
Wet scrubber (WS)					
Packed bed/packed tower		€37282-191,000	€52191-170330		EPA[41] [42]
Spray-chamber/ Spray-tower		€2659-$13800	€5264-104180		
Use of Clean Fuels (FC-fuel choice)					
Fuel switch to natural gas	Other solid fuels			€/MW	AMEC 2014
	1-5MW$_{th}$			€35289	
	5-20MW$_{th}$			€45034	
	20-50MW$_{th}$			€50192	

---

[40] https://www3.epa.gov/ttn/catc/cica/files/fcyclon.pdf

[41] https://www3.epa.gov/ttn/catc/cica/files/fpack.pdf

[42] https://www3.epa.gov/ttn/catc/cica/files/fsprytwr.pdf

Appendix 5- Engine types

This section describes the main stationary engine technologies used for the combustion of liquid and gaseous fuels. Stationary engines can be divided **according to fuel used** into:

(a) Diesel engines (inclusive dual fuel high pressure gas diesel (GD));
(b) Spark plug or by other device ignited gas engines (SG); and
(c) Dual fuel engines (low pressure gas DF).

Also, stationary engines can be divided **into 2- and 4-stroke** engines.

(a) 2-stroke engines with compression or open chamber ignition and combustion are low speed engines (<300 rpm) and can be either one or (high pressure gas) dual fuel (GD) solutions;
(b) 4-stroke engines are ignited with compression, pilot, spark or hot body principle, they have open chamber, pre-chamber, lambda 1 or lean-burn combustion solutions and are either medium (300 < n < 1200 rpm) or high speed (> 1200 rpm) engines.

Different engine solutions are such as gas-fired spark ignited (SG), dual fuel low pressure gas (DF) or high pressure gas diesels (GD) or liquid fired diesel or DF engines;

In addition, stationary engines can also be divided **according to their speed**:

(a) The low-speed and medium-speed engines are often used in e.g. base load, decentralized small/medium sized combined heat and power (CHP), gas compression and crude oil pumping and grid peaking plant applications. Low and medium speed engines can operate either in one or dual fuel principle;
(b) Low speed 2-stroke engines (available up to about 90 MWe unit sizes) operate on liquid distillate fuel oil, HFO (heavy fuel oil), residual, emulsified fuel oil, refinery vacuum residuals and high pressure natural gas (GD type);
(c) Medium speed 4-stroke engines (available up to about 25 MWe diesel engines), up to about 17 MWe low pressure gas dual fuel (DF) and spark ignition (SG) up to about 10 MWe unit sizes) operate on liquid distillate fuel oil and HFO (diesel and dual fuel engines), liquid residual fuel oil, emulsified fuel oils, refinery vacuum residuals (diesel engines), natural gas (gas diesel (GD), dual fuel (DF) and spark ignition (SG) types), biogas, mining and landfill gas (depending on SG and GD types);
(d) High-speed engines are mostly used in peak load applications. High-speed stationary engine types are usually small (unit size output up to a 5 MWe) and mostly operate on natural gas, biogas, landfill gas, liquid bio-fuels and liquid distillate fuel oil.

High-speed engines are used both in electricity production and in other non-road applications

Appendix 6- References

Author	Year	Title	Link
Aarhus Univ.	2014	Danish emission inventories from stationary combustion plants	http://dce2.au.dk/pub/SR102.pdf
AEAT/ DG env	2004	Costs and environmental effectiveness of options for reducing air pollution from small-scale combustion installations	http://ec.europa.eu/environment/archives/cafe/pdf/final_report_aeat.pdf
Amec	2012	Collection and analysis of data to support Commission in reporting in line with Article 73(2) of Directive 2010/75/EU on industrial emissions on the need to control emissions from the combustion of fuels in installations with a total rated thermal input below 50 MW	https://circabc.europa.eu/sd/a/cf89c7cb-a4e1-4f18-8a74-33f7987bb4b0/30310%20Final%20Report%20(Combustion).pdf
Amec	2014	Analysis of the impact of various options to control emissions from the combustion of fuels in installations with TRTI<50MW	
Canada Gov	2016	Canada regulation for stationary engines	https://laws-lois.justice.gc.ca/eng/regulations/SOR-2016-151/
Carb	2010	Analysis of the Technical Feasibility and Costs of After-Treatment Controls on New Emergency Standby Engines	https://www.arb.ca.gov/regact/2010/atcm2010/atcmappb.pdf
CITEPA	2005	Wood Combustion in Domestic Appliances	https://www.citepa.org/old/forums/egtei/2-domestic_wood_appliances_version2_12-10-05.pdf
Danish EPA	2013	Technical review – Catalogue of reduction technologies	https://www.danskehavne.dk/wp-content/uploads/2015/11/partnerskab-for-reneres-skibsfart-technical-review-catalogue-of-reduction-technologies.pdf
Defra	2016	Amendments to environmental permitting regulations to improve air quality by transposition of Medium Combustion Plant Directive and application of emission controls to high NOx generators in anticipation of the 2020 NOx emission ceiling within the Gothenburg Protocol	https://consult.defra.gov.uk/airquality/medium-combustion-plant-and-controls-on-generators/supporting_documents/Impact%20Assessment.pdf
DG Env	2005	Ship Emissions: Assignment, Abatement and Market-based Instruments	http://ec.europa.eu/environment/air/pdf/task2_nox.pdf
DG JRC	2007	Small combustion installations: techniques, emissions and measures for emission reduction	http://publications.jrc.ec.europa.eu/repository/bitstream/JRC42208/reqno_jrc42208_final%20version%5b2%5d.pdf
DG JRC	2017	LCP BREF	http://eippcb.jrc.ec.europa.eu/reference/BREF/LCP/JRC_107769_LCPBref_2017.pdf
EC	2015	MCPD	http://ec.europa.eu/environment/industry/stationary/mcp.htm

Author	Year	Title	Link
ECN	2008	Calculations to support Dutch Emission Limits Combustion Plants Decree (BEES B)	https://www.ecn.nl/docs/library/report/2008/e08020.pdf
EGTEI	2014	Estimation of cost of reduction techniques for LCPs-Examples	shared RicardoBox
EGTEI	2014	Estimation of cost of reduction techniques for LCPs-Methodology	shared RicardoBox
EGTEI	2014	New EGTEI cost calculation sheet	shared RicardoBox
EGTEI	2011	Costs for SCR systems for stationary engines in a study by EGTEI	http://www.unece.org/fileadmin/DAM/env/documents/2011/eb/wg5/WGSR49/Informal%20docs/17_EGTEI-Cost-stationary-engines-UNECE-06-04-2011.pdf
energia	2015	Finish Industrial sector position on MCP regulation	https://energia.fi/files/512/MCP_Particle_Emission_Reduction_13.6.2014_FINAL.pdf
Euromot	2013	Comments regarding the review of smaller combustion plants carried out under the IED	https://www.euromot.eu/wp-content/uploads/2017/03/EU_IED_Review_plants_smaller_than_50_MW_2013-01-04.pdf
EUROMOT	2018	Recommendations on Collecting and Evaluating Information on the Environmental Performance of Technologies used in Medium Combustion Plants (MCP) and Energy Efficiency	Shared drive - provided by WG members
EUROMOT	2013	Euromot position on MCPD pre-study	https://www.euromot.eu/wp-content/uploads/2017/03/EU_IED_Review_plants_smaller_than_50_MW_2013-01-04.pdf
GAO	2012	Air Emissions and Electricity Generation at U.S. Power Plants	https://www.gao.gov/assets/600/590188.pdf
GE Turbines		Gas Turbine NOx Emissions Approaching Zero – Is it Worth the Price?	https://www.ge.com/content/dam/gepower-pgdp/global/en_US/documents/technical/ger/ger-4172-gas-turbine-nox-emissions-approaching-zero-worth-price.pdf
GE Turbines	visited 2019	World firts flange flange replacement	https://www.genewsroom.com/press-releases/worlds-first-flange-flange-replacement-ge-frame-6b-gas-turbine-cuts-emissions-extends
GE Turbines	visited 2019	GE rejuvenates spanish cogen plant	https://www.genewsroom.com/press-releases/ge-rejuvenates-spanish-cogeneration-plant-with-repowering-in-place-upgrade-217528
GE Turbines	visited 2019	GE power brochure	https://www.ge.com/content/dam/gepower-pgdp/global/en_US/documents/product/2016-gas-power-systems-products-catalog.pdf

Author	Year	Title	Link
Holzkurier	2015	Brennen tut‘s gut	Shared drive - provided by WG members
Icct	2014	Feasibility of IMO Annex VI Tier III implementation using Selective Catalytic Reduction	https://www.theicct.org/sites/default/files/publications/ICCT_MarineSCR_Mar2014.pdf
IIASA		Nitrogen oxides emissions, abatement technologies and related costs for Europe in the RAINS model database	http://www.iiasa.ac.at/~rains/reports/noxpap.pdf
Inerco	2018	Inerco: tec combustion y depuracion gases	shared RicardoBox
irbea	2016	Study on biomass combustion emissions	http://www.irbea.org/wp-content/uploads/2016/12/IrBEA-BiomassEmissionsReportAndAppendices.pdf
KTH univ.	2009	Introduction of water to reduce NOx emissions	https://www.econologie.com/fichiers/partager3/144467016792Duad.pdf
LFL Tier und Technik	2016	Energetische Effizienz und Emissionen der Biogasverwertung	shared RicardoBox
MAN/RR	2018	Cumplimiento limites emision	shared RicardoBox
MTU	2018	Emission and the new generation series 4000 for Natural Gas	shared RicardoBox
MWM	2018	MW Solutiones tecnicas para reduccion de emisionesde gases escape motores MWM	shared RicardoBox
NL ministry	2018	NL regulations MCPs: READER overview	shared RicardoBox
NL ministry	2013	Evaluatie Besluit emissie	shared RicardoBox
NL ministry	2013	De mogelijke aanscherping van vijf eisen in het Besluit	shared RicardoBox
NL ministry	2013	Evaluation of the Dutch Decree on Emissions	shared RicardoBox
NL Ministry	2008	Onderbouwing actualisatie BEES	shared RicardoBox
Ricardo	2017	Technical support for developing the profile of certain categories of Large Combustion Plants regulated under the Industrial Emissions Directive	https://circabc.europa.eu/w/browse/49c16bc4-83d3-45a0-9e8c-0450b0f3435f
saica	2018	2017 Sustainibility report	https://www.saica.com/wp-content/uploads/2018/11/Memoria-de-Sostenibilidad2017_Grupo-Saica_ING_Baja.pdf
Solar Turbines	2017	Available SoLoNOx Emissions Options	shared RicardoBox
Solar Turbines	2018	SCR Capex Opex	shared RicardoBox
Solar Turbines	2011-draft	Typical NOx Warranty Level Options at Full Load, ISO Conditions	shared RicardoBox
Swedish Environmental Protection Agency	2018	Swedish implementation of the MCP Directive	shared RicardoBox
Swedish Environmental Protection Agency	2018	Swedish implementation of the MCP Directive (introduction)	shared RicardoBox

Author	Year	Title	Link
Swedish Environmental Protection Agency	2018	Svensk författningssamling	shared RicardoBox
Swedish Environmental Protection Agency	2018	Swedish Nox emissions MCP	shared RicardoBox
Swedish Environmental Protection Agency	2018	Survey Swedish MCP	shared RicardoBox
SwissPower	2006	Ein Gemeinschafts projekt de Waldeigentumer und Energiedienstleiter	shared RicardoBox
TÜV NORD Umweltschutz	2016	Wintershall Holding GmbH	shared RicardoBox
TÜV NORD Umweltschutz	2016	ExxonMobil Osterwald	shared RicardoBox
TÜV NORD Umweltschutz	2018	ExxonMobil Ruhrleermoor 1	shared RicardoBox
TÜV NORD Umweltschutz	2018	ExxonMobil Ruhrleermoor 2	shared RicardoBox
UBA	2018	Verordnung über mittelgroße Feuerungsanlagen	shared RicardoBox
AEAT/ DG env	2004	Costs and environmental effectiveness of options for reducing air pollution from small-scale combustion installations	http://ec.europa.eu/environment/archives/cafe/pdf/final_report_aeat.pdf
A. Franco	2011	Analysis of small size combined cycle plants based on the use of supercritical HRSG	https://www.researchgate.net/publication/251667915_Analysis_of_small_size_combined_cycle_plants_based_on_the_use_of_supercritical_HRSG
Norewian government	Visited March 2019	The NOx fund	https://www.nho.no/samarbeid/nox-fondet/the-nox-fund/articles/technologies-and-suppliers/
Yang et al.	2012	Selection of techniques for reducing shipping NOx and SOx emissions, Transportation Research	https://www.researchgate.net/publication/257547651_Selection_of_techniques_for_reducing_shipping_NOx_and_SOx_emissions
EEA	2014	Damage cost function factors	http://www.externe.info/
Manieniyan V	2013	Experimental Analysis of Exhaust Gas Recirculation on DI Diesel Engine Operating with Biodiesel	https://www.researchgate.net/publication/266672529_Experimental_Analysis_of_Exhaust_Gas_Recirculation_on_DI_Diesel_Engine_Operating_with_Biodiesel
WÄRTSILÄ	2014	WÄRTSILÄ 2-STROKE DUAL FUEL TECHNOLOGY	https://www.sintef.no/globalassets/upload/marintek/cimac2014/6---2-s-df-technology-cimac-norway-jan-22-2014.pdf
E.A. Yfantis	2016	Green transportation: "NOx Reduction Technologies for Marine Diesel Engines"	http://www.ashrae.gr/GrT2016/GrT2016_Yfantis.pdf
NREL	2003	Gas-fired distributed energy resource. Technology characterisation	https://www.nrel.gov/docs/fy04osti/34783.pdf
UK GOV Departmen of energy and climate change	2008	CHP technology	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/345189/Part_2_CHP_Technology.pdf

Ricardo
Energy & Environment

The Gemini Building
Fermi Avenue
Harwell
Didcot
Oxfordshire
OX11 0QR
United Kingdom
t: +44 (0)1235 753000
e: enquiry@ricardo.com

ee.ricardo.com