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Determination of emission factors and emissions in 2020 and 2030 for oil- and gas-fired combustion plants not requiring a permit in the scope of the EU Directive on medium combustion plants

Final Report

by:

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Determination Of Emission Factors For Oil And Gas Combustion Plants Not Requiring A Permit And Under The Scope Of The EU Directive On Medium Combustion Plants

This report documents the results of a research project that included 100 measurements of emissions from medium combustion plants with a nominal heat output of 1 MW to less than 10 MW. Emissions of nitrogen oxides, carbon monoxide, dust, TOC, methane, NMVOC and the smoke number (in the case of oil combustion) were measured at 28 fuel oil and 72 natural gas plants. Mean values and maxima of the measured parameters were documented, and correlations of the parameters were analysed.

Emission factors were calculated based on the measurement results and other measurement data for emissions of nitrogen oxides, carbon monoxide, methane, NMVOC and dust. Total emissions were calculated for Germany in 2020 and projected for 2030 in two scenarios. The emissions for nitrogen oxides from natural gas plants (98 % of total) resulted for 2020 in around 8700 tonnes. A reduction to about 6,500 tonnes is expected for 2030 (-25 %). If a limit value were set as introduced in the Netherlands, nitrogen oxides emissions would fall to about 3900 tonnes in 2030 (-55 %). Additionally, emission calculations for 2020 were less than 12 tonnes of dust (12 tonnes in 2030), less than 103 tonnes of methane (92 tonnes in 2030), and about 1500 tonnes of carbon monoxide (1300 tonnes in 2030). NMVOC emissions were calculated with zero.

Furthermore, best available techniques for emission reduction were documented. The information was based on literature research as well as on interviews and a workshop with manufacturers, the association of manufacturers and authorities. In addition, the report documents regulatory requirements for medium combustion plants with a rated thermal input of 1 MW to less than 10 MW in six European countries (Austria, Flanders/Belgium, Denmark, Germany, the Netherlands, and Switzerland).

Ermittlung von Emissionsfaktoren für nicht genehmigungsbedürftige Öl- und Gasfeuerungen im Geltungsbereich der EU-Richtlinie über mittelgroße Feuerungsanlagen

Der vorliegende Bericht zeigt die Ergebnisse eines Forschungsprojektes, in dem 100 Messungen an mittelgroßen Feuerungsanlagen mit 1 MW bis unter 10 MW Nennwärmeleistung durchgeführt wurden. Dabei wurden Emissionen von Stickstoffoxiden, Kohlenmonoxid, Staub, Gesamtkohlenstoff, Methan, NMVOC und (bei Ölfeuerung) der Rußzahl bei 28 Heizöl- und 72 Erdgasfeuerungen gemessen. Mittelwerte und Maxima der gemessenen Parameter wurden dokumentiert und Korrelationen der Parameter untereinander analysiert.

Aus den Messergebnissen und weiteren Messdaten wurden Emissionsfaktoren gebildet und Emissionen von Stickstoffoxiden, Kohlenmonoxid, Methan, NMVOC sowie Staub für Deutschland im Jahr 2020 berechnet und für das Jahr 2030 in zwei Szenarien abgeschätzt. Die Emissionen für Stickstoffoxide aus Erdgasfeuerungen (98 % der Gesamtemissionen) lagen im Jahr 2020 bei rund 8.700 Tonnen. Für das Jahr 2030 ist eine Senkung auf rund 6.500 Tonnen zu erwarten (-25 %). Würde für Erdgasfeuerungen ein Grenzwert wie in den Niederlanden festgelegt, würden die Stickstoffoxid-Emissionen auf rund 3.900 Tonnen im Jahr 2030 sinken (-55 %). Für 2020 ergaben sich aus den Anlagen weniger als 12 Tonnen Staubemissionen (12 Tonnen in 2030), weniger als 104 Tonnen Methan-Emissionen (93 Tonnen in 2030), rund 1.500 Tonnen Kohlenmonoxid-Emissionen (1.300 Tonnen in 2030) und keine NMVOC-Emissionen.

Weiterhin wurden beste verfügbare Techniken zur Emissionsminderung dokumentiert. Als Grundlage dienten Literaturrecherchen sowie Interviews und ein Workshop mit Herstellern, dem Verband der Hersteller sowie Behörden. Zusätzlich dokumentiert der Bericht regulative Vorgaben für mittelgroße Feuerungsanlagen mit 1 MW bis unter 10 MW Feuerungswärmeleistung in sechs europäischen Ländern (Flandern/Belgien, Dänemark, Deutschland, Niederlande, Österreich und der Schweiz).

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List of abbreviations

AISV	Plant-related air quality control / accident prevention committee (Ausschuss Anlagenbezogener Immissionsschutz / Störfallvorsorge)
AT	Austria
BAT	Best available techniques
BE	Belgium
BDH	Federal Association of the German Heating Industry (Bundesverband der deutschen Heizungsindustrie)
BGBl.	Federal Law Gazette (Bundesgesetzblatt)
BImSchG	Federal Air Quality Control Act (Bundes-Immissionsschutzgesetz)
BImSchV	Federal Ordinance on Air Quality Control (Bundes-Immissionsschutzverordnung)
BY	Bavaria (Bayern)
C	Carbon
CH	Switzerland
CH_4	Methane
CHP	Combined heat and power plant
CO	Carbon monoxide
DE	Germany (Deutschland)
DIBt	German Institute for Building Technique (Deutsches Institut für Bautechnik)
DIN	German Institute for Standardisation (Deutsches Institut für Normung)
DK	Denmark
EC	European Community
EL	Extra light
EN	European standard
EU	European Union
EUR	Euro
FKZ	Research identifier (Forschungskennzeichen)
FWL	Rated thermal input
HE	Hesse (Hessen)

HH	Hamburg
K	Kelvin
KÜO	Sweeping and inspection regulations (Kehr- und Überprüfungsordnung)
LAI	Federal/State Working Group for Air Quality Control (Bund/Länder-Arbeitsgemeinschaft für Immissionsschutz)
LANUV	State Agency for Nature, Environment and Consumer Protection (Landesamt für Natur, Umwelt und Verbraucherschutz)
LfU	State Office for the Environment (Landesamt für Umwelt)
LfULG	State Office for Environment, Agriculture and Geology (Landesamt für Umwelt, Landwirtschaft und Geologie)
LNG	Liquefied natural gas
LOQ	Limit of quantification
MCPD	Medium Combustion Plants Directive
MU	Measurement uncertainty
MW	Megawatt
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne (Statistical classification of economic activities in the European Community)
NEC	National Emission Ceilings
NH_3	Ammonia
NI	Lower Saxony (Niedersachsen)
NL	The Netherlands
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen oxides
NO_2	Nitrogen dioxide
NRW	North Rhine-Westphalia (Nordrhein-Westfalen)
n. s.	not specified
O_2	Oxygen
PM	Particulate Matter

PJ	Petajoule
SCR	Selective Catalytic Reduction
SN	Saxony (Sachsen)
SNCR	Selective Non-Catalytic Reduction
ST	Saxony-Anhalt (Sachsen-Anhalt)
S	Sulphur
SO_2	Sulphur dioxide
TJ	Terajoule
TOC	TOC
VOC	Volatile organic compounds
UBA	German Environment Agency (Umweltbundesamt)
UM	Ministry of the Environment (Umweltministerium)
ZIV	Federal Association of Chimney Sweeps - Central Guild Association (Bundesverband des Schornsteinfegerhandwerks – Zentralinnungsverband)

Summary

In Germany, there are about 13,000 medium oil and gas combustion plants with a rated thermal input of 1 MW to less than 10 MW. In 2020, about 25 % of the plants was fired with fuel oil, and about 75 % with natural gas. Some of the natural gas-fired plants are equipped with dual-fuel burners and can be converted to fuel oil operation. (ZIV 2020)

Oil and gas combustion plants with a rated thermal input of 1 MW to less than 10 MW that do not require a permit fall within the scope of EU Directive 2015/2193 (EU Directive 2015). The Directive was transposed into national law in Germany by the "Ordinance on Medium Combustion, Gas Turbine and Internal Combustion Engine Plants" (44. BImSchV 2019), so that plants must comply with corresponding requirements.

The aim of the research project was to estimate the emissions from fuel oil and natural gas combustion plants with a rated thermal input of 1 MW to less than 10 MW that do not require a permit for the year 2020, to calculate a projection of the emissions from these plants for the year 2030, and to determine best available techniques for these facilities.

For this purpose, 100 measurements of the following air pollutants were carried out: Nitrogen oxides (NO_x), carbon monoxide (CO), total dust, methane (CH_4), total organic hydrocarbons (TOC). In addition, the smoke number was measured in fuel oil plants in order to analyse correlations with dust emissions. Based on these measurements and on additional data, emission factors were calculated that best represent the current stock of medium oil and gas combustion plants with a rated thermal input of 1 MW to less than 10 MW.

The measurements were carried out in combustion plants of housings and of industrial sites. In order to select the plants, contact was made with authorities as well as with companies in the housing sector, with heat contractors and with industry.

The main obstacle to participation of plants in the measurements was the lack of suitable measurement openings in the flue gas system with a size of three inches. This is not necessary for the measurements required so far. The vast majority of plants with a rated thermal input of 1 MW to less than 10 MW only have openings with a size of ½ inch, which are suitable for measurements by the chimney sweepers, but were not sufficient for the measurement programme of the research project.

The measurements took place in the period from November 2020 to April 2022 at 50 plants that are used by contracting companies to mainly heat residential buildings and at 29 plants that provide process heat at industrial sites. 21 plants have multi-fuel burners, so that both gas and oil combustion could be measured at one plant. 51 plants have single-fuel burners for gas, seven plants have single-fuel burners for fuel oil. In addition to the measurements on existing plants, five new gas-fired plants as defined by the 44th BImSchV were also measured, in other words plants that were installed from 20 December 2018 and therefore have to comply with a stricter limit value for carbon monoxide and for nitrogen oxides.

The comparison of the shares of the measured plants with the total number of installed plants in Germany shows that the plants with a low nominal heat output (1 - < 2 MW) are somewhat less represented in the sample of measured plants than in the total number of plants, both for oil-fired and gas-fired plants. Plants with a higher nominal heat output (4 - < 5 MW and 5 - < 10 MW) are somewhat higher represented in the sample of measured plants. In the other groups of nominal heat output, the share of the measured plants roughly corresponds to the share of totally installed plants (Table 10 and Table 11).

Table 1: Number and share of measured oil-fired plants compared with the inventory of plants in Germany, grouped by nominal heat output

Nominal power Fuel oil plants	1 - < 2 MW	2 - < 3 MW	3 - < 4 MW	4 - < 5 MW	5 - < 10 MW	Total
Measured plants	12	5	1	5	5	28
Total plants installed	1904	635	237	145	256	3177
Share of measured plants	43 %	18 %	3 %	18 %	18 %	100 %
Share of total plants installed	60 %	20 %	7 %	5 %	8 %	100 %

Source plants inventory: ZIV (2020)

Table 2: Number and proportion of measured gas-fired plants compared with the inventory of plants in Germany, grouped by nominal heat output

Nominal heat output Gas-fired plants	1 - < 2 MW	2 - < 3 MW	3 - < 4 MW	4 - < 5 MW	5 - < 10 MW	Total
Measured plants	25	18	7	12	10	72
Total plants installed	5310	1876	718	494	1018	9416
Share of measured plants	35 %	25 %	10 %	16 %	14 %	100 %
Share of total plants installed	56 %	20 %	8 %	5 %	11 %	100 %

Source plants inventory: ZIV (2020)

For each plant a measurement report was prepared by the measuring institute, containing measurement results, conversions of the measurement results to standard conditions and reference oxygen content, as well as comments on specific measurement conditions, in particular the duct properties and the operating mode (especially load and load fluctuations).

In addition, a questionnaire was completed by the operators for each plant on technical data (especially on emission reduction techniques) and on fuel consumption. In the absence of other data, the recorded fuel consumption was used to extrapolate the energy consumption of all plants in Germany with a rated thermal input of 1 MW to less than 10 MW.

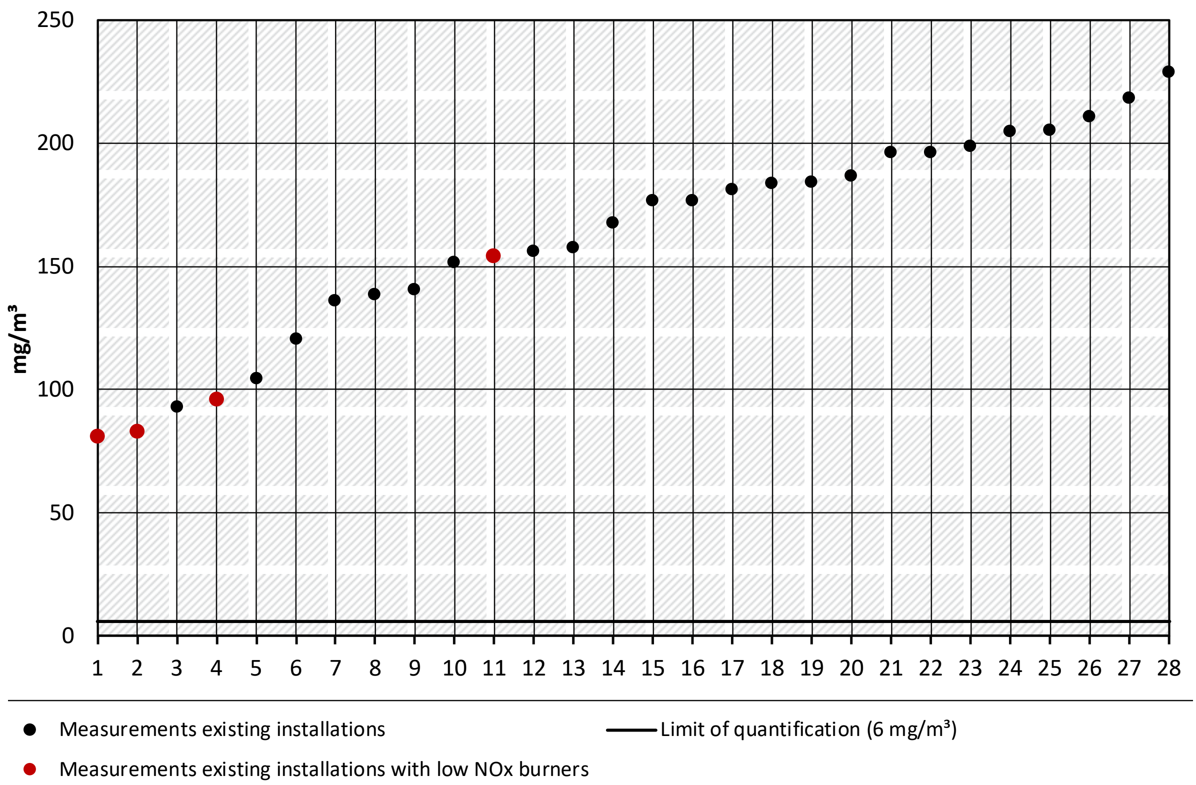
If possible, three uninterrupted half-hourly measurements were taken at each plant. In cases where a plant was running at low or no load due to load fluctuations, the measurement was interrupted in order to achieve a total of three 30-minute measurement periods. In a few individual cases, the duration of the individual measurements had to be shortened, but a minimum measurement duration of 20 minutes was always guaranteed.

The measurements show very low emissions for dust, methane and total organic hydrocarbons (TOC), which in many cases were below the limit of quantification of the measurement methods. The NMVOC emission values calculated from methane and TOC were zero, so it can be assumed that the organic hydrocarbon emissions, if they are above the limit of quantification, consist entirely of methane.

The 28 measurements in fuel oil plants resulted in smoke number values of 0.04 to 1.5. For the analysis of the correlation of smoke number and dust concentration, 21 pairs of measurements with measurement results above the limit of quantification were available. The resulting correlation factor was 0.39, so that no correlation could be determined.

The 28 measurements of nitrogen oxides at fuel oil plants resulted in emission values between 81 and 229 mg/Nm³. No value was below the limit of quantification (6 mg/Nm³). (Figure 1)

Figure 1: **Nitrogen oxides measurement results - fuel oil plants (standardised, 3 % reference oxygen content, mean value of three measurements, usually 30 minutes each)**

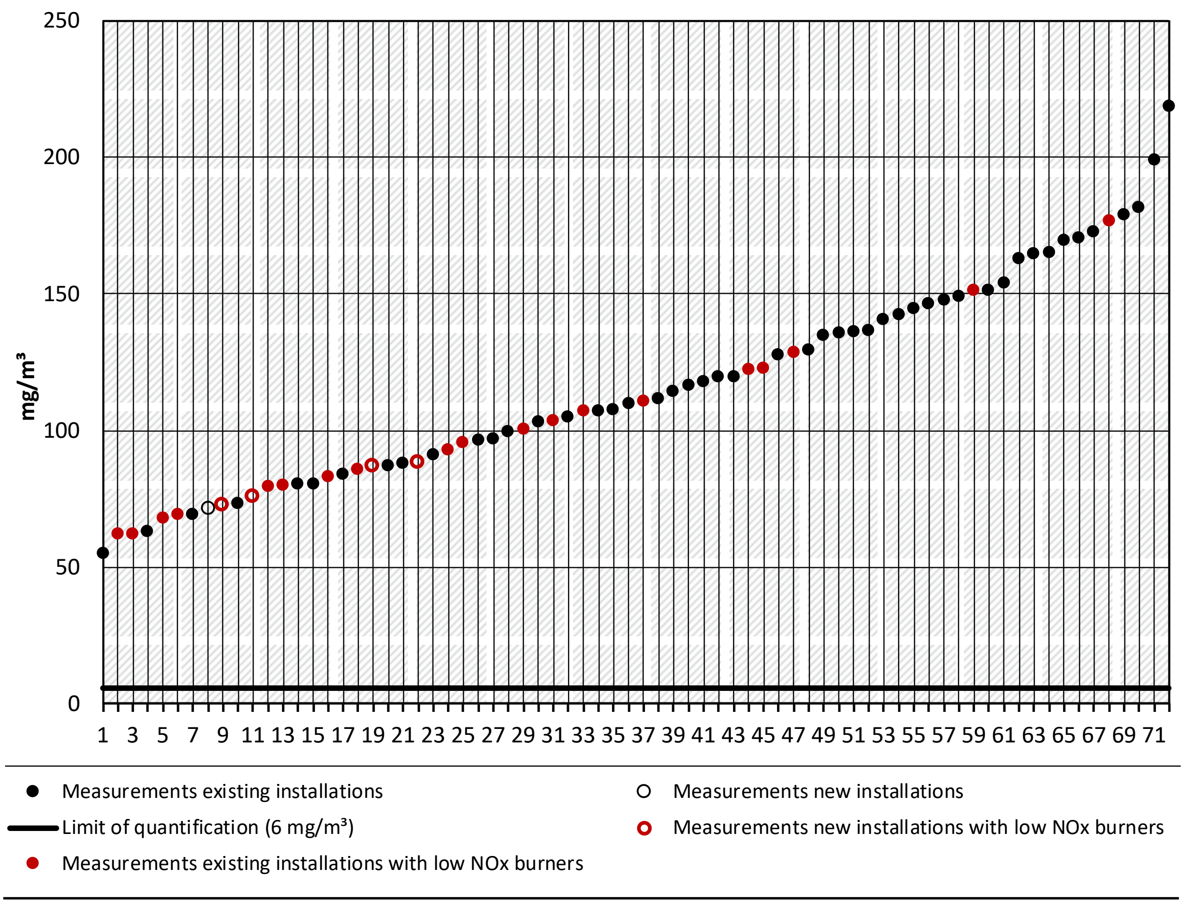


Existing installations started operation before 20 december 2018.

Source: own figure (Ökopol)

The 72 measurements of nitrogen oxides at natural gas plants resulted in emission values between 56 and 220 mg/Nm³. No value was below the limit of quantification (6 mg/Nm³). (Figure 2 where five measurements on new combustion plants are indicated with circular markings).

Figure 2: Nitrogen oxides measurement results - natural gas plants (standardised, 3 % reference oxygen content, mean value of three measurements, usually 30 minutes each)



Existing installations started operation before 20 december 2018.

Source: own figure (Ökopol)

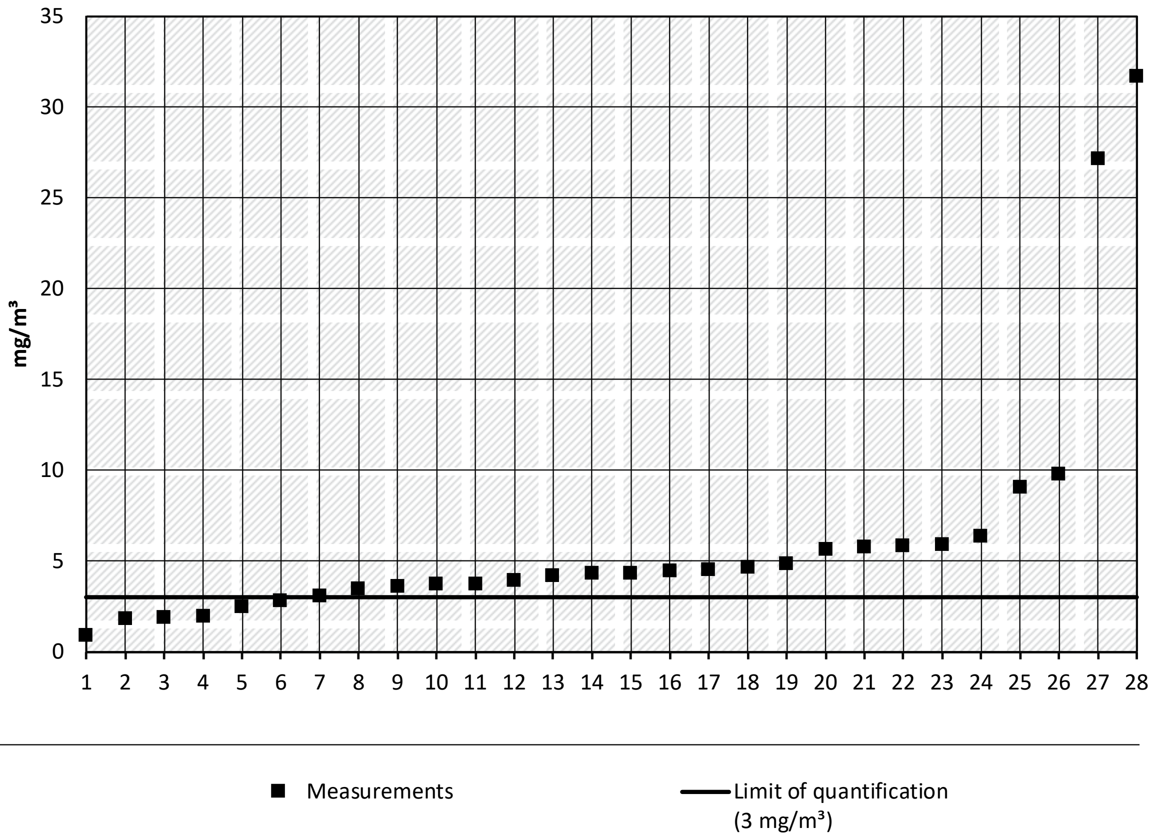
The natural gas combustion plants with low NO_x burners achieved the lowest NO_x values. There is no correlation between the NO_x values and the age of the plant, neither for fuel oil plants nor for the existing natural gas plants. The measurements of five new natural gas plants (installed from 20.12.2018) showed low NO_x values.

When determining emission factors for nitrogen oxides, two values from natural gas plants were not included in the calculation because measurements showed unusually high CO, TOC and methane values and the assessment was that with the small number of measured values, it could not be assumed that the two measurements were representative of the total number of plants (see Chapter 2).

The 28 measurements of carbon monoxide at fuel oil plants resulted in emission values between 0.90 and 31 mg/Nm³. Except for two particularly high values, all values were below 10 mg/Nm³. Six values (21 %) were below the limit of quantification (3 mg/Nm³). (Figure 3)

The two highest CO values (27/32 mg/Nm³) were measured on plants installed in 1991 and 1993, respectively, showing high load variations and average loads of only 20 and 30 %. In both cases, a particularly high smoke number was also measured; in one case, relatively high emissions of methane (1.8 mg/Nm³) and TOC (1.4 mg/Nm³) were observed.

Figure 3: Carbon monoxide measurement results - fuel oil plants (standardised, 3 % reference oxygen content, mean value of three measurements, usually 30 minutes each)

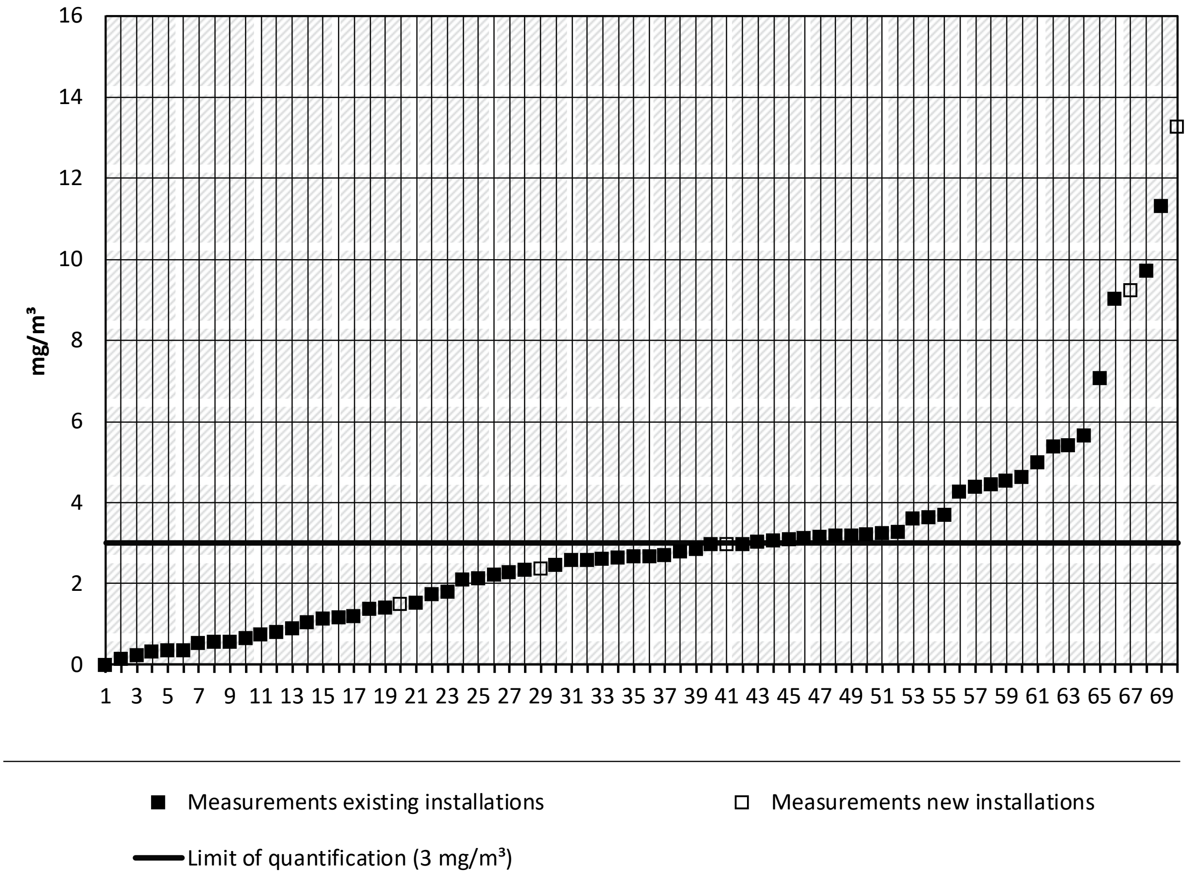


Source: own figure (Ökopol)

The 72 measurements of carbon monoxide at natural gas plants resulted in emission values between 0 and 2761 mg/Nm³. With 42 values, more than half of the measured values (58 %) were below the limit of quantification (3 mg/Nm³). Except from two particularly high values (1240/2761 mg/Nm³) and two other elevated values, measurement results were all below 10 mg/Nm³. (Figure 4, not showing the two highest values).

The two highest values (1240/2762 mg/Nm³) were measured at plants installed in 2001. During the measurement, they were operated with an average load of 65 and 29 %, respectively. The measured values indicate a suboptimal combustion, as particularly high values for TOC (93/594 mg/Nm³) and methane (98/603 mg/Nm³) were also measured at the same time, as well as a particularly high value for dust (1.6 mg/Nm³) in one case.

Figure 4: Carbon monoxide measurement results - natural gas plants (without two highest values; standardised, 3 % reference oxygen content, mean value of three measurements, usually 30 minutes each)



Existing installations started operation before 20 december 2018.

Source: own figure (Ökopol)

For the calculation of the emission factor for carbon monoxide, the measurement data set was significantly smaller than the data already available at the German Environment Agency (UBA 2023a). The highest emission values measured in the project have a considerable influence on the mean value of the measurements (especially in the case of measurements at natural gas plants), whereby it is unclear whether such high individual values are representative for a larger data collective. Therefore, the own measurement data were not used for the emission calculation.

When determining the emission factors, the measurement results for natural gas plants were weighted according to the recorded annual operating hours of the respective plants in order to better reflect in the emission factor the emissions of plants with a longer operating time. In the case of fuel oil plants, weighting did not make sense because the plants were predominantly equipped with dual-fuel burners and had no or only very few operating hours for fuel oil.

Table 3 and Table 4 document the average emission concentrations determined for existing fuel oil plants and natural gas plants in 2020, in other words for plants installed before 20 December 2018. For more detailed reporting, the data is presented separately according to the rated thermal input of 1 MW to less than 5 MW and of 5 MW to less than 10 MW.

Table 3: Average emission concentrations at 3 % O_2 for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for existing fuel oil plants with 1 - < 10 MW in 2020

Rated thermal input [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	22	164	< 0.961	0.00	< 0.646
5 - < 10	34	150	< 1.16	0.00	< 1.00

Note: If a value is marked with "<", measured values were below the limit of quantification and were included in the average emission concentration with half the limit of quantification. No weightings were made according to annual operating hours, as a large proportion of the fuel oil plants had no or only very few operating hours.
Source: CO data 2019 (UBA 2023a), other data own measurements (2020-2022)

Table 4: Average emission concentrations at 3 % O_2 for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for existing natural gas plants with 1 - < 10 MW in 2020

Rated thermal input [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	19	116	< 1,15	0,00	< 0,136
5 - < 10	21	125	< 1,93	0,00	< 0,0493

Note: If a value is marked with "<", the measured value was below the limit of quantification and is included in the average emission concentration with half the limit of quantification. All values except for CO are based on own measurement data and were weighted according to the annual operating hours of the measured plants.
Source: CO data 2019 (UBA 2023a), other data from own measurements (2020-2022)

With the exception of nitrogen oxides and carbon monoxide, for new fuel oil plants and natural gas plants with a rated thermal input of 1 MW to less than 10 MW, the same emission concentrations were assumed as for existing plants. For these other pollutants (TOC, NMVOC and dust), it is assumed that the emission behaviour of new plants does not improve or change significantly.

For carbon monoxide emissions, the emission concentrations reported by Germany to the EU according to Article 11 (2) of the MCPD by 1 January 2021 were used. They were calculated on one hand from measurement results of the Bavarian Chimney Sweepers Association for 3,475 natural gas and 1,524 fuel oil plants, and on the other hand from federal states' databases of measurements at 490 medium combustion plants requiring a permit (321 natural gas and 169 fuel oil plants). (UBA 2023a)

For nitrogen oxide emissions from new fuel oil plants, a NOx measurement value was used resulting from at a plant with 3.2 MW, installed in 2018. (Table 5)

Table 5: Average emission concentrations at 3 % O_2 for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for new fuel oil plants with 1 - < 10 MW

Rated thermal input [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	21	92.9	< 0.961	0	< 0.646
5 - < 10	21	92.9	< 1.160	0	1.00

Note: If a value is marked with "<", the measured values were below the limit of quantification and are included in the average emission concentration with half the limit of quantification. All values except for CO are based on own

measurement data. No weighting was done according to annual operating hours, since a large part of the fuel oil plants had no or only very few operating hours. Only the average emission concentration for NOx is based on the measurement of a newer plant built in 2018. The average emission concentrations for CH_4, NMVOC and dust correspond to the values for existing plants, as no relevant changes are assumed for these parameters in newer plants.
Source: CO data from 2019 (UBA 2023a), other data from own measurements (2020-2022)

Two scenarios are calculated for nitrogen emissions from natural gas plants: Scenario 1 uses the mean nitrogen oxides value for new plants from own measurements of five new plants with a nominal heat output of 1 MW to less than 5 MW (installed in 2019 or 2020). (Table 6)

Table 6: Average emission concentrations at 3 % O_2 for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for new natural gas plants with 1 - < 10 MW, scenario 1

Rated thermal input [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	19	78.9	< 1.15	0.00	< 0.136
5 - < 10	16	78.9	< 1.93	0.00	< 0.0493

Note: If a value is marked with "<", the measured values were below the limit of quantification and are included in the average emission concentration with half the limit of quantification. All values except for CO are based on own measurement data and weighted according to the annual operating hours of the measured plants; only the value for NOx is based on the measurement at five new plants built in 2019 and 2020. The average emission concentrations for CH_4, NMVOC and dust correspond to the average emission concentration for existing plants, as no relevant changes are assumed for these parameters at new plants.
Source: CO data from 2019 (UBA 2023a), other data own measurements (2020-2022)

For scenario 2 (Table 7), it is assumed that in 2030 a limit value for nitrogen oxides corresponding to the regulation in the Netherlands must be complied with in new and existing natural gas plants in Germany. The NOx limit value in the Netherlands for natural gas combustion plants with 1 - <10 MW is 70 mg/Nm³, whereby the measurement uncertainty is deducted for compliance with the limit value. According to the measurement data from the Netherlands (SCIOS 2022), this corresponds approximately to a NOx emission limit value of 100 mg/Nm³, if the measurement uncertainty is added to the measured value, as specified in Germany in the 44th BImSchV for compliance with the limit value.

Table 7: Average emission concentrations at 3 % O_2 for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for natural gas plants with 1 - < 10 MW at NOx limit value specification like in the Netherlands

Rated thermal input [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	19	59.1	< 1.15	0.00	< 0.136
5 - < 10	16	59.1	< 1.93	0.00	< 0.0493

Note: If a value is marked with "<", the measured values were below the limit of quantification and are included in the average emission concentration with half the limit of quantification. The own measured values used for average emission concentrations (CH_4, NMVOC, dust) were weighted according to the annual operating hours of the measured plants.
Source: CO data from 2019 (UBA 2023a), NOx data 2017-2022 (SCIOS 2022), other data own measurements 2020-2022

To calculate the total emissions of oil and gas plants with a rated thermal input of 1 MW to less than 10 MW, the energy consumption of the plants is needed to multiply an "activity rate" by the emission factor. In the absence of other data, energy consumption was based on the energy consumption data collected during the project's 100 measurements. The mean fuel consumption per installed capacity of the measured plants [MJ/MW] was extrapolated to the total number of plants in Germany using the inventory data of the Chimney Sweeper Association (ZIV 2019).

For the year 2020, this results in an energy consumption of 266,132 TJ from fuel oil and natural gas consumption in plants with a rated thermal input of 1 MW to less than 10 MW in Germany. Gas consumption has a share of 99.4 %, fuel oil consumption a share of 0.6 %.

The projection for 2030 results in a 10.9 % lower energy consumption of 237,013 TJ fuel oil and natural gas in plants with a rated thermal input of 1 MW to less than 10 MW in 2030 compared to 2020. Gas consumption has a share of 99.4 % and fuel oil consumption a share of 0.6 %. For energy consumption in 2030, in accordance with the "Projection Report 2021" (Repenning et al. 2021) prepared on behalf of the German Environment Agency, it was assumed that consumption of fuel oil will remain unchanged compared to 2020 and that consumption of natural gas will fall by 11 % from 2020 to 2030.

The average emission concentrations [mg/Nm^3] were converted using the factor 0.28 to obtain emission factors [kg/TJ]. To calculate total emissions, the factors were multiplied with the energy consumption. In the calculations for the years 2020 and 2030, the share of new plants was taken into account. For new plants, a lower emission factor than for existing plants was applied for CO and NOx emissions.

The data of the ZIV (2019) show that in the years 2015 to 2019, on average about 2 % of fuel oil plants and 3 % of natural gas plants were renewed annually in relation to the total stock. Therefore, it was assumed for the year 2020 that the new plants constructed in 2019 and 2020 account for about 4 % of the fuel oil and 6 % of the natural gas plants. Accordingly, for the year 2030, it was assumed that new plants built from 2019 to 2030 account for 24 % of fuel oil plants and 36 % of natural gas plants.

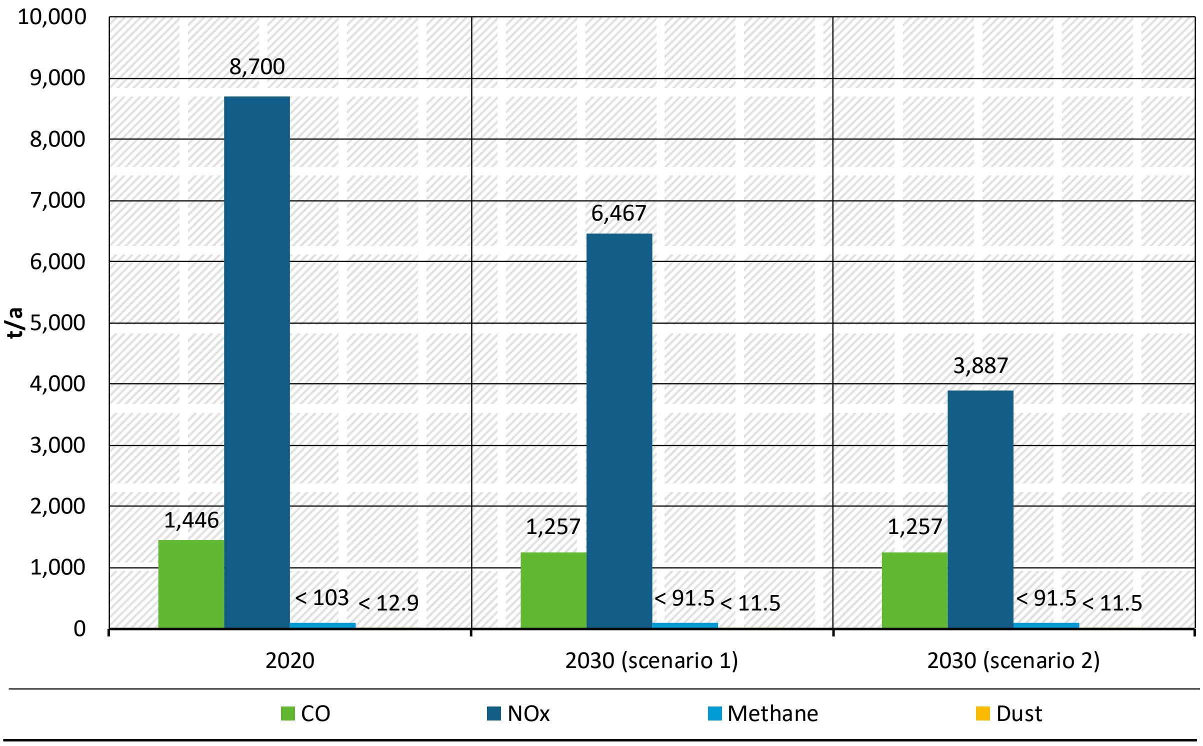
Figure 5 shows the calculated emissions from natural gas plants with a rated thermal input of 1 MW to less than 10 MW in Germany in the years 2020 to 2030. For 2030, scenario 1 shows the calculated development without a change in the NO_x limit value, while scenario 2 shows the development with the specification of a limit value of 100 mg/Nm^3 instead of 150 mg/Nm^3, which must be complied with by adding the measurement uncertainty.

For 2020, for natural gas plants, emissions of nitrogen oxides were calculated with about 8,700 tonnes. For 2030, an emission reduction to about 6,500 tonnes is expected (-25 %). If an emission limit value would be fixed on the level required in the Netherlands, nitrogen oxides emissions would fall to about 3,900 tonnes (-55 %).

Additionally, calculations for natural gas plants for 2020 were less than 13 tonnes of dust emissions (12 tonnes in 2030), less than 103 tonnes of methane emissions (92 tonnes in 2030) and about 1,400 tonnes of carbon monoxide emissions (1,300 tonnes in 2030). NMVOC emissions were calculated with zero.

For fuel oil plants, calculations for 2020 and 2030 resulted in about 65 tonnes of nitrogen oxides emissions, about 10 tonnes of carbon monoxide emissions, less than 0.5 tonnes for both methane and dust emissions, and no NMVOC emissions.

Figure 5: Development of emissions from natural gas plants with a rated thermal input of 1 MW to less than 10 MW in Germany from 2020 to 2030



Note: Methane, dust with "<" as measurement results were partly below the limit of quantification (LOQ) and used for the emission factor with half the LOQ.

Source: own figure (Ökopol)

In addition to the emission calculation, research was carried out on best available techniques in oil- and gas-fired plants with a rated thermal input of 1 MW to less than 10 MW. For this purpose, interviews were conducted with manufacturers, associations and authorities, and a technical workshop was carried out.

Table 8 lists the emission reduction techniques reported by the operators for the measured plants. The completeness of the information depended on the knowledge of the responsible contact person. By assisting the manufacturers in the analysis of burner types based on the photos of burner nameplates, it was possible to identify additional burners with NO_x abatement technique that were not reported by the operators (BDH 2022). There is a possibility that further operator information on emission abatement techniques is incomplete, as not all burner nameplates were accessible for photos or were from manufacturers who did not participate in the nameplate analysis.

Based on 100 measurements in 79 plants, the use of low NO_x burners for nitrogen oxides reduction was documented in 27 plants (34 %). About a quarter of these low NO_x burners were retrofitted in existing plants. Six of the 27 plants were reported to have low NO_x burners and flue gas recirculation for nitrogen oxides reduction.

Of a total of 28 plants with fuel oil combustion where a measurement was carried out, ten plants (36 %) indicated that low-sulphur fuel oil was used. It should be taken into account that seven of the ten plants use multi-fuel burners that were predominantly operated with gas until 2021 and thus tended to have older fuel oil stocks.

Lambda sensors or O_2 controls, which result in a better burnout and thus lower emissions of CO, methane and TOC, were documented at nine of the 79 plants (11 %). Waste heat utilisation leading to specifically lower total emissions was reported by the operators at 19 of the 79 plants (24 %).

A combination of techniques was rarely mentioned: Two plants have low NO_x burners and O_2 control.

Table 8: Information on emission reduction techniques installed at the measured plants

Emission reduction technique	Purpose of the technique	Tech-niques when installed	Tech-niques as retrofit	Existing plants (before 20.12.2018)	New-plants (from 20.12.2018)	Multi-fuel combus-tion plants
Low NO_x burner	Reduction of nitrogen oxides	21	6	24	3	4
Waste gas recirculation	Reduction of nitrogen oxides, burnout improved	1	5	6	0	1
Low sulphur fuel oil	Reduction of sulphur oxides	-	-	10	0	7
Lambda sensor / O_2 control	Improvement of fuel use and burnout, thereby reduction of CO, methane and NMVOC	7	2	9	0	1
Waste gas heat use / heat exchanger	Improved fuel use, thus lower specific emissions	no data	no data	19	4	2

Source: Operator questionnaires of 79 plants (own survey), manufacturer data on 21 burners (BDH 2022).

Furthermore, research was carried out in several European countries on the setting of emission limit values, in particular on diverging measurement requirements and the way of compliance with limit values.

Table 18 provides an overview of the respective emission limit values and measurement requirements of medium combustion plants in six selected European countries.

The data in the table show that the limit values and measurement requirements of the selected countries differ significantly. This also applies to the parameters to be measured. Flanders requires additional compliance with limit values for sulphur dioxides and dust for natural gas firing plants. In addition to CO, NOx, dust or the smoke number, Flanders also requires compliance with two limit values for heavy metals (vanadium and nickel) for fuel oil and other liquid fuels.

Furthermore, there is a significant difference in the evaluation of the measurement results. On the one hand, the measurement uncertainty is taken into account differently. In Austria and the Netherlands, for example, the measurement uncertainty has to be subtracted, in Germany and Flanders it must be added. On the other hand, in some countries the mean value of the measurements can be compared with the limit value, in other countries every measured value must comply with the emission limit value. The requirements on measurement periods also differ between quarterly, annual, biennial and triennial.

Table 9: Requirements on medium combustion plants in Flanders/Belgium, Denmark, Switzerland, Austria, Germany, and the Netherlands

	Flanders (1-20 MW)	DK (< 10 MW)	CH (< 10 MW)	AT (1-20 MW)	DE (1-10 MW)	NL (1-20 MW)
Limit values Natural gas (range min.-max.)[2] [mg/Nm³]	NOx: 80-300 CO: 100-250 SO_2: 35 Dust: 5-50	NOx: 100-105 CO: 125	NOx: 80 CO: 100 NH_3: 30	NOx: 100-120 CO: 80	NOx: 100-150 CO: 80-110	NOx: 70
Limit values fuel oil (range min.-max.)[1] [mg/Nm³]	NOx: 185-650 CO: 175-250 SO_2: 170-1700 Dust: 5-200 Nickel: 3 Vanadium: 5	NOx: 180 CO: 165	NOx: 80 CO: 100 NH_3: 30 Smoke number: 1	NOx: 150 CO: 80 Dust: 10-20	NOx: 200 CO: 80-150 Smoke number: 1	NOx: 120 SO_2: 200 Dust: 5
Requirement regarding the measurement uncertainty	Addition	Not considered	Subtraction	Subtraction	Addition	Subtraction
Uncertainty of measurement max.	All parameters: 30 %	-	-	NOx: 20 % CO: 10 % Dust: 30 %	-	NOx: 20 % SO_2: 20 % Dust: 30 %
Number and duration of measurements	One measurement (60 min. or 90 min.)	2 x 45 minutes	3 x 30 minutes	3 x 30 minutes	3 x 30 minutes	3 x 30 minutes
Limit value adjustment	Mean of all measured values	Mean of all measured values	Mean of all measured values	Each individual value	Each individual value	Each individual value
Measurement periods (only plants with > 500 annual operating hours)	Every 2 years for 1 - < 5 MW Every 3 months for 5 - < 20 MW	Every 2 years for < 5 MW Yearly for 5 - < 10 MW and > 3000 hours/a	Every 2 years	Every 3 years	Every 3 years	Every 3 years for new plants Once for existing plants (and every 3 y. from 2025 for > 5 MW and from 2030 for 1 -5 MW)

Source: UBA workshop (2022)

[1] The emission limit values (given in ranges) depend on the plant capacity, the operating hours and the date of the first permit (existing/new).

Zusammenfassung

In Deutschland gibt es etwa 13.000 mittelgroße Öl- und Gasfeuerungsanlagen mit einer Nennwärmeleistung von 1 MW bis unter 10 MW. Mit Heizöl wurden 2020 etwa 25 % der Anlagen gefeuert, mit Erdgas etwa 75 %. Teilweise sind die erdgasgefeuerten Anlagen mit Zweistoffbrennern ausgerüstet und können auf Heizölbetrieb umgestellt werden. (ZIV 2020)

Nicht genehmigungsbedürftige Öl- und Gasfeuerungsanlagen mit 1 MW bis unter 10 MW Feuerungswärmeleistung fallen in den Geltungsbereich der EU-Richtlinie 2015/2193 („MCPD") (EU-Richtlinie 2015). Die Richtlinie ist in Deutschland durch die „Verordnung über mittelgroße Feuerungs-, Gasturbinen- und Verbrennungsmotoranlagen" (44. BImSchV 2019) in nationales Recht umgesetzt, so dass die Anlagen entsprechende Vorgaben einzuhalten haben.

Ziel des Forschungsvorhabens war es, die Emissionen von nicht genehmigungsbedürftigen Heizöl- und Erdgasfeuerungen für das Jahr 2020 abzuschätzen, die besten verfügbaren Techniken für diese Anlagen zu ermitteln sowie eine Prognose der Emissionen aus diesen Anlagen für das Jahr 2030 zu berechnen.

Dafür erfolgten 100 Messungen zu folgenden Luftschadstoffparametern: Stickstoffoxide (NO_x), Kohlenmonoxid (CO), Gesamtstaub, Methan (CH_4), Summe organischer Kohlenwasserstoffe (Gesamt C). Zusätzlich wurde bei Ölfeuerungen die Rußzahl gemessen, um Korrelationen mit den Staubemissionen zu ermitteln. Auf Basis dieser Messungen und weiterer Daten wurden Emissionsfaktoren berechnet, die in Deutschland den aktuellen Bestand mittelgroßer Öl- und Gasfeuerungsanlagen mit 1 MW bis unter 10 MW Feuerungswärmeleistung bestmöglich repräsentieren.

Die Messungen erfolgten in Anlagen der Wohnungswirtschaft und in Industriebetrieben. Zur Auswahl der Anlagen erfolgte die Kontaktaufnahme mit Behörden sowie mit Firmen der Wohnungswirtschaft, des Wärme-Contractings und der Industrie.

Haupthindernis für eine Teilnahme der Anlagen an den Messungen war das Fehlen einer geeigneten Messöffnung an der Abgasanlage mit einer Größe von drei Zoll. Diese ist für die bisher erforderlichen Messungen nicht notwendig. Die große Mehrheit der Anlagen mit einer Feuerungswärmeleistung von 1 MW bis unter 10 MW weist lediglich Öffnungen mit einer Größe von ½ Zoll auf, die zwar für Messungen durch das Schornsteinfegerhandwerk geeignet sind, aber für das Messprogramm des Forschungsvorhabens nicht ausreichend waren.

Die Messungen fanden im Zeitraum November 2020 bis April 2022 an 50 Anlagen statt, die durch Contracting-Firmen überwiegend zur Beheizung von Wohngebäuden dienen, und an 29 Anlagen, die Prozesswärme in einem Industriebetrieb bereitstellen. Bei 21 Anlagen handelt es sich um Anlagen mit Mehrstoffbrennern, so dass sowohl Gas- als auch Öl-Feuerung an einer Anlage gemessen werden konnte. 51 Anlagen verfügen über Einstoffbrenner für Gas, sieben Anlagen über Einstoffbrenner für Heizöl. Zusätzlich zu den Messungen an bestehenden Anlagen wurden auch fünf gasbetriebene neue Anlagen im Sinne der 44. BImSchV gemessen, das heißt Anlagen, deren Inbetriebnahme ab dem 20. Dezember 2018 erfolgte und die daher einen strengeren Grenzwert für Kohlenmonoxid und für Stickstoffoxide einhalten müssen.

Der Vergleich der Anteile der gemessenen Anlagen mit dem Anlagenbestand in Deutschland zeigt, dass die Anlagen mit geringer Leistung (1 MW - < 2 MW) im gemessenen Anlagenmix sowohl bei Ölfeuerung als auch bei Gasfeuerung etwas geringer vertreten sind als im Gesamtbestand der Anlagen; Anlagen mit größerer Leistung (4 MW - < 5 MW und 5 MW - < 10 MW) sind in den gemessenen Anlagen anteilig etwas stärker vertreten. In den übrigen Leistungsbereichen stimmen die Anteile der gemessenen Anlagen in etwa mit den Anteilen im Gesamtbestand der Anlagen überein (Tabelle 10 und Tabelle 11).

Tabelle 10: Anzahl und Anteil gemessener Anlagen mit Ölfeuerung im Vergleich mit dem Gesamtbestand in Deutschland, gruppiert nach Nennwärmeleistung

Nennleistung Energieträger	1 - < 2 MW	2 - < 3 MW	3 - < 4 MW	4 - < 5 MW	5 - < 10 MW	Summe
Heizölfeuerungen (gemessene Anlagen)	12	5	1	5	5	28
Heizölfeuerungen (gesamte Anlagen)	1.904	635	237	145	256	3.177
Heizölbetrieb (Anteil gemessen)	43 %	18 %	3 %	18 %	18 %	100 %
Heizölbetrieb (Anteil gesamt)	60 %	20 %	7 %	5 %	8 %	100 %

Quelle: Gesamtanlagenbestand: ZIV (2020)

Tabelle 11: Anzahl und Anteil gemessener Anlagen mit Gasfeuerung im Vergleich mit dem Gesamtbestand in Deutschland, gruppiert nach Nennwärmeleistung

Nennwärmeleistung Energieträger	1 - < 2 MW	2 - < 3 MW	3 - < 4 MW	4 - < 5 MW	5 - < 10 MW	Summe
Erdgasfeuerungen (gemessene Anlagen)	25	18	7	12	10	72
Erdgasfeuerungen (gesamte Anlagen)	5.310	1876	718	494	1.018	9.416
Erdgasfeuerungen (Anteil gemessene)	35 %	25 %	10 %	16 %	14 %	100 %
Erdgasfeuerungen (Anteil gesamt)	56 %	20 %	8 %	5 %	11 %	100 %

Quelle Gesamtanlagenbestand: ZIV (2020)

Von jeder Anlage wurde vom Messinstitut ein Messprotokoll angefertigt, das Messergebnisse, Umrechnungen der Messergebnisse auf Normbedingungen und Bezugssauerstoffgehalt sowie Anmerkungen zu Besonderheiten bei der Messung enthielt, insbesondere zur Beschaffenheit der Messstrecke und zu Besonderheiten der Messung (vor allem Last und Lastschwankungen).

Zusätzlich wurde von den Betreibern zu jeder Anlage ein Fragebogen zu technischen Daten (insbesondere zu Emissionsminderungstechniken) und zu Brennstoffverbräuchen ausgefüllt. Mangels anderer Daten dienten die erfassten Brennstoffverbräuche zur Hochrechnung des Energieverbrauchs aller Anlagen in Deutschland mit einer Leistung von 1 MW bis unter 10 MW.

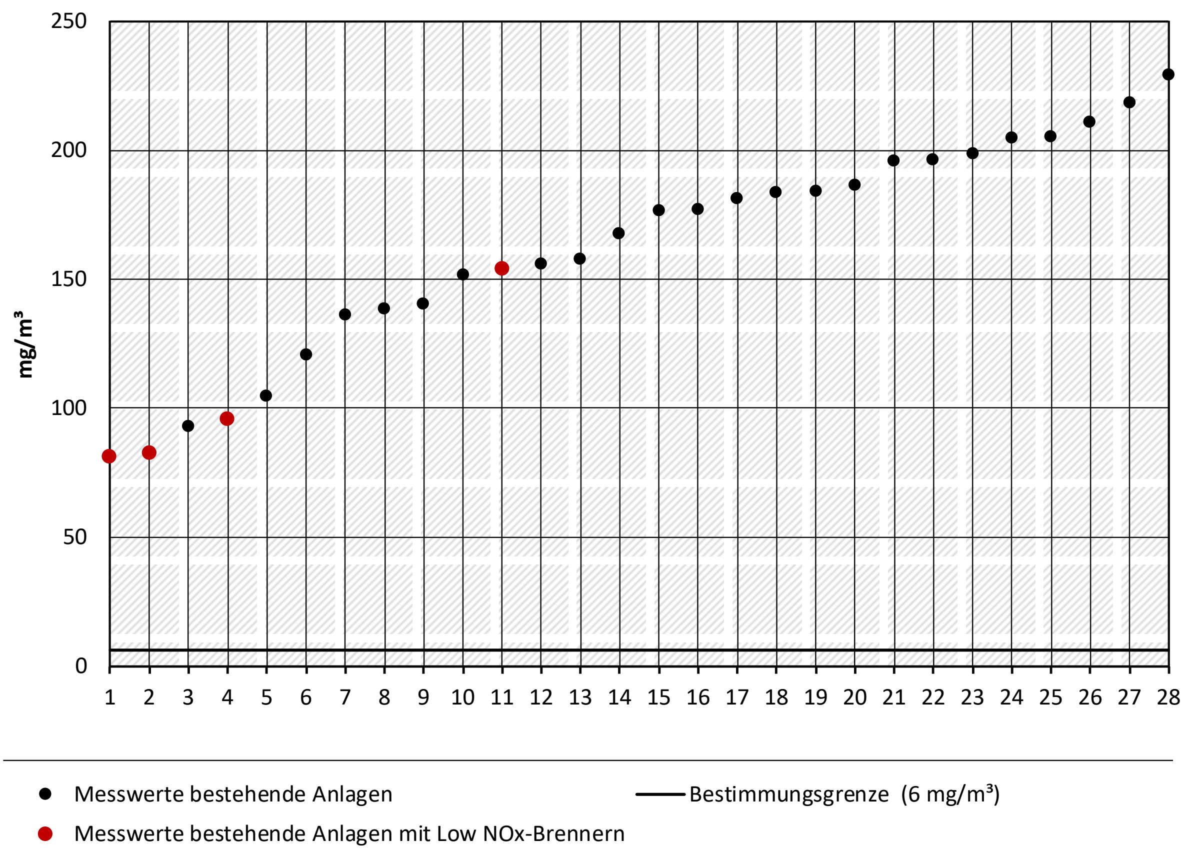
An jeder Anlage erfolgten möglichst drei ununterbrochene halbstündige Messungen. In Fällen, in denen eine Anlage aufgrund von Lastschwankungen mit geringer oder fehlender Auslastung lief, wurde die Messung unterbrochen, um möglichst in Summe dreimal 30 Minuten Messzeit zu erreichen. In wenigen Einzelfällen musste die Dauer der Einzelmessungen verkürzt werden, wobei eine Mindestmessdauer von 20 Minuten stets gewährleistet war.

Die Messungen zeigen für Staub, Methan und die Summe organischer Kohlenwasserstoffe (Gesamt-C) sehr niedrige Emissionen, die vielfach unterhalb der Bestimmungsgrenze der Messmethoden lagen. Die aus Methan und Gesamt-C berechneten NMVOC-Emissionswerte lagen bei null, so dass davon auszugehen ist, dass die Emissionen organischer Kohlenwasserstoffe, wenn sie im messbaren Bereich liegen, vollständig aus Methan bestehen.

Die 28 Messungen an Heizölfeuerungen ergaben Rußzahl-Werte von 0,04 bis 1,5. Für die Analyse der Korrelation von Rußzahl und Staubkonzentration lagen 21 Messwertpaare vor, die über der Bestimmungsgrenze lagen. Der resultierende Korrelationsfaktor beträgt 0,39, so dass keine Korrelation festgestellt werden konnte.

Die 28 Messungen von Stickstoffoxiden an Heizölfeuerungen ergaben Emissionswerte zwischen 81 und 229 mg/Nm³. Kein Wert lag unter der Bestimmungsgrenze (6 mg/Nm³). (Abbildung 6)

Abbildung 6: Stickstoffoxide-Messwerte – Heizöl-Feuerung (normiert, 3 % Bezugssauerstoffgehalt, Mittelwert aus drei Messungen je in der Regel 30 Minuten)

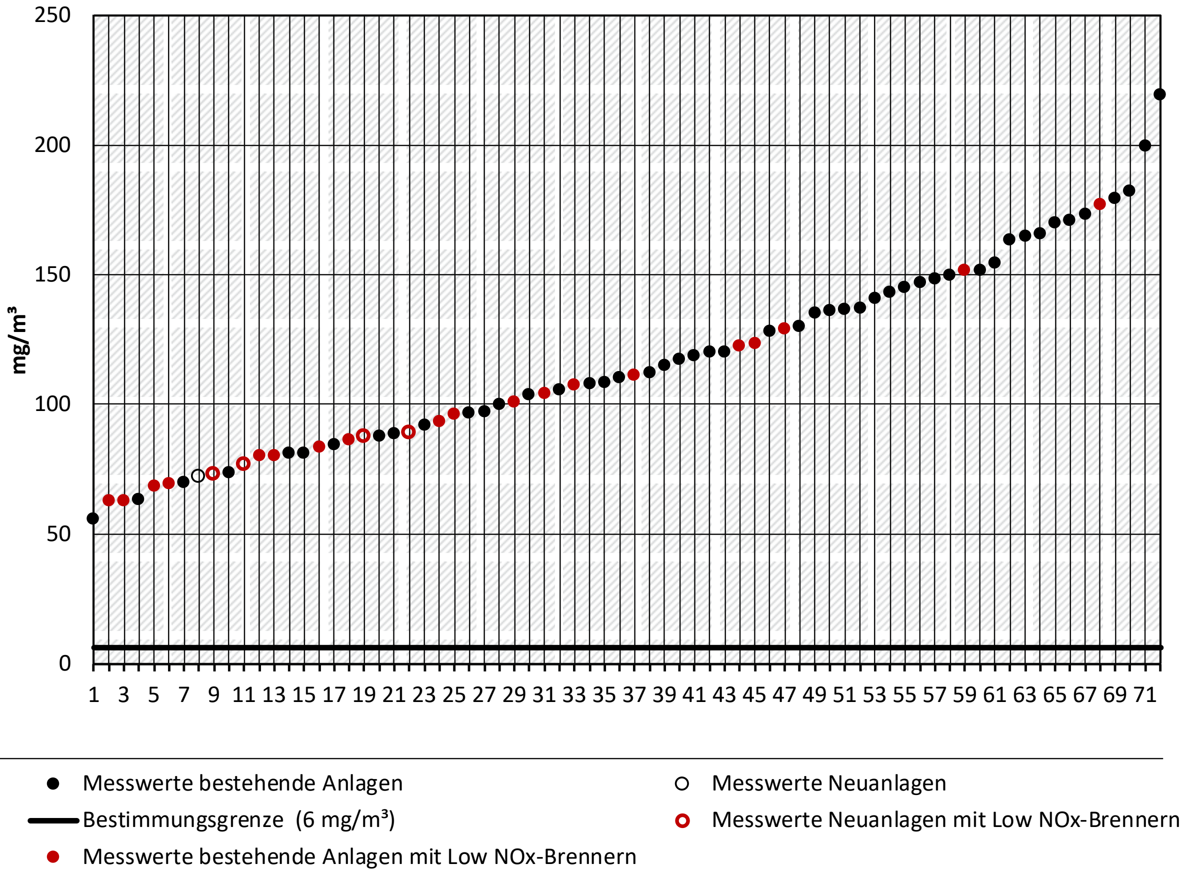


Bestehende Anlagen wurden vor dem 20. Dezember 2018 in Betrieb genommen.

Quelle: eigene Darstellung (Ökopol)

Die 72 Messungen von Stickstoffoxiden an Erdgasfeuerungen ergaben Emissionswerte zwischen 56 und 220 mg/Nm³. Kein Wert lag unter der Bestimmungsgrenze (6 mg/Nm³). (Abbildung 7, in der die fünf Messungen an Neuanlagen mit kreisförmigen Markierungen gekennzeichnet sind).

Abbildung 7: Stickstoffoxide-Messwerte – Erdgas-Feuerung (normiert, 3 % Bezugssauerstoffgehalt, Mittelwert aus drei Messungen je in der Regel 30 Minuten)



Bestehende Anlagen wurden vor dem 20. Dezember 2018 in Betrieb genommen.

Quelle: eigene Darstellung (Ökopol)

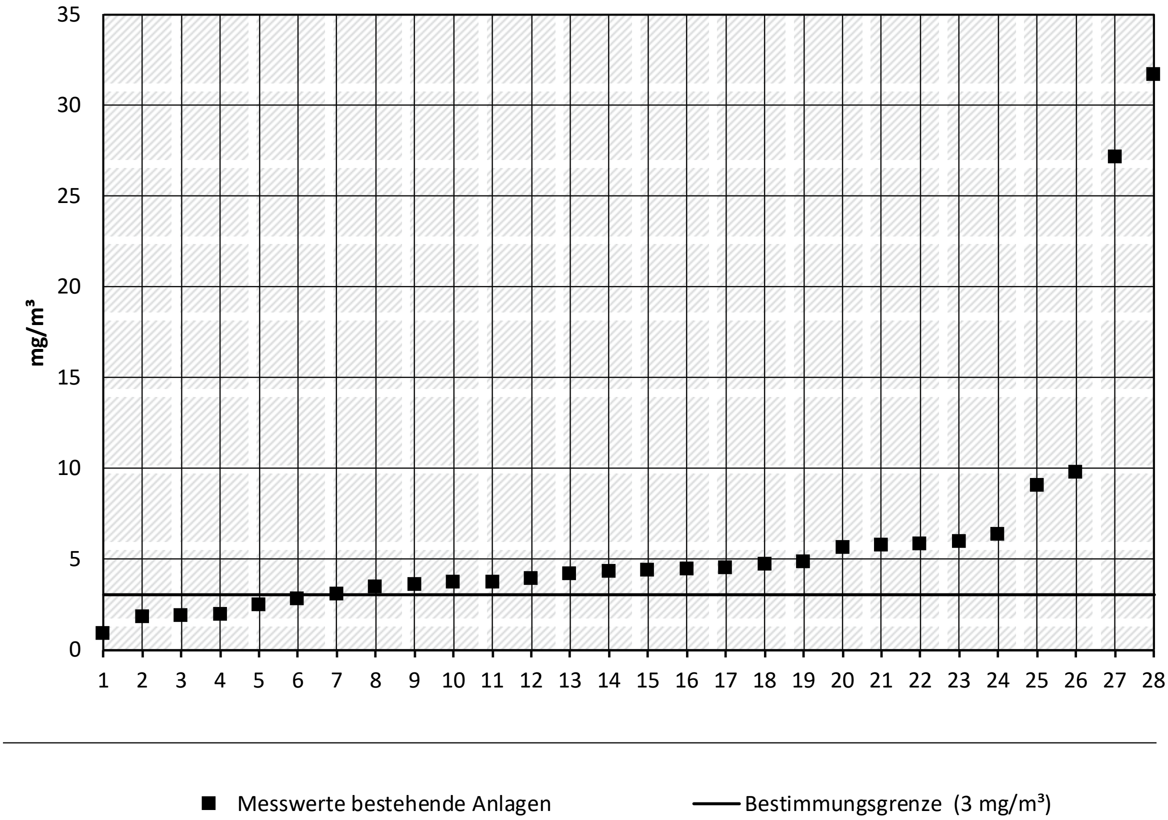
Die Erdgasfeuerungen mit Low NO_x-Brennern erreichten die niedrigsten NO_x-Werte. Eine Korrelation der NO_x-Messwerte mit dem Anlagenalter besteht weder bei Heizölfeuerungen noch bei den bestehenden Erdgasfeuerungen. Die fünf gemessenen neuen Erdgasfeuerungen (Inbetriebnahme ab 20.12.2018) weisen niedrige NO_x-Messwerte auf.

Bei der Ermittlung von Emissionsfaktoren für Stickstoffoxide wurden zwei Werte aus Erdgas-Anlagen nicht in die Berechnung einbezogen, da bei der Messung ungewöhnlich hohe CO-, Gesamtkohlenstoff- und Methanwerte gemessen wurden und die Einschätzung bestand, dass bei der geringen Anzahl von Messwerten nicht davon ausgegangen werden kann, dass die Werte der Anlage für das Gesamtspektrum der Anlagen repräsentativ sind (siehe Kapitel 2).

Die 28 Messungen von Kohlenmonoxid an Heizölfeuerungen ergaben Emissionswerte zwischen 0,90 und 32 mg/Nm³. Abgesehen von zwei besonders hohen Werten lagen alle Werte unter 10 mg/Nm³. Sechs Werte (21 %) lagen unter der Bestimmungsgrenze (3 mg/Nm³). (Figure 19)

Die beiden höchsten CO-Werte (27/32 mg/Nm³) wurden an Kesseln mit Baujahr 1991 und 1993 gemessen, und zwar bei starker Taktung der Kessel und einer mittleren Last von lediglich 20 bzw. 30 %. In beiden Fällen wurde auch eine besonders hohe Rußzahl gemessen; in einem Fall relativ hohe Emissionen von Methan (1,8 mg/Nm³) und Gesamt-Kohlenstoff (1,4 mg/Nm³).

Abbildung 8: Kohlenmonoxid-Messwerte – Heizöl-Feuerung (normiert, 3 % Bezugssauerstoffgehalt, Mittelwert aus drei Messungen je in der Regel 30 Minuten)



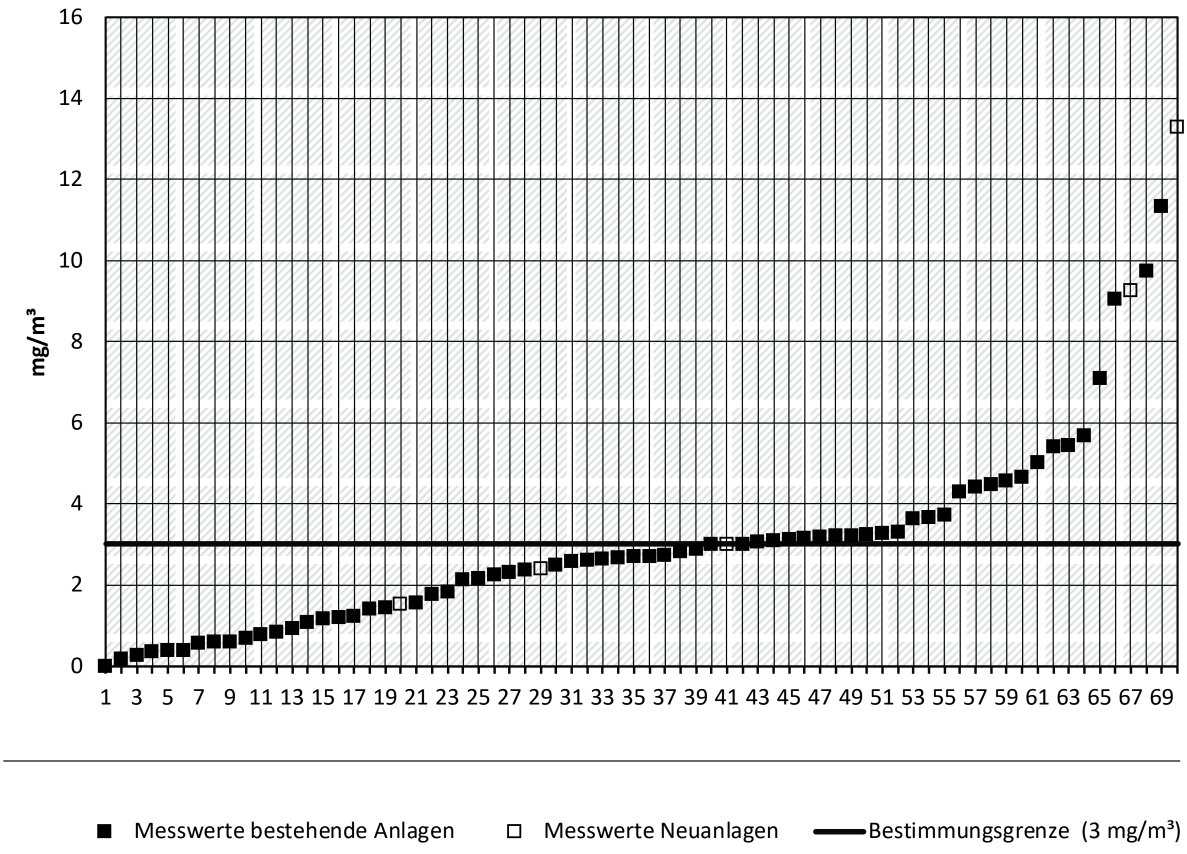
Bestehende Anlagen wurden vor dem 20. Dezember 2018 in Betrieb genommen

Quelle: eigene Darstellung (Ökopol)

Die 72 Messungen von Kohlenmonoxid an Erdgasfeuerungen ergaben Emissionswerte zwischen 0 und 2761 mg/Nm³. Mit 42 Werten lag mehr als die Hälfte der Messwerte (58 %) unter der Bestimmungsgrenze (3 mg/Nm³). Abgesehen von zwei besonders hohen Werten (1240/2761 mg/Nm³) und zwei weiteren erhöhten Werten wurden Werte unter 10 mg/Nm³ gemessen. (Figure 21 ohne die zwei höchsten Werte).

Die beiden höchsten Werte (1.240/2.762 mg/Nm³) wurden an Anlagen gemessen, die im Jahr 2001 installiert wurden. Sie wurden während der Messung mit einer mittleren Last von 65 bzw. 29 % betrieben. Die Messwerte weisen auf eine suboptimale Brennereinstellung hin, da gleichzeitig auch besonders hohe Werte für Gesamt-Kohlenstoff (93/594 mg/Nm³) und Methan (98/603 mg/Nm³) gemessen wurden, sowie in einem Fall auch ein besonders hoher Wert für Staub (1,6 mg/Nm³).

Abbildung 9: Kohlenmonoxid Messwerte – Erdgas-Feuerung (ohne zwei höchste Werte; normiert, 3 % Bezugssauerstoffgehalt, Mittelwert aus drei Messungen je in der Regel 30 Minuten)



Bestehende Anlagen wurden vor dem 20. Dezember 2018 in Betrieb

Quelle: eigene Darstellung (Ökopol)

Für die Berechnung des Emissionsfaktors für Kohlenmonoxid war das erhobene Datenkollektiv deutlich kleiner als beim Umweltbundesamt bereits vorliegende Daten (UBA 2023a). Die im Projekt gemessenen besonders hohen Emissionswerte beeinflussen den Mittelwert der Messungen erheblich (insbesondere bei Messungen an Erdgas-Anlagen), wobei unklar ist, ob derartig hohe Einzelwerte auch für ein größeres Datenkollektiv repräsentativ sind. Daher wurden die eigenen Messdaten für die Emissionsberechnung nicht verwendet.

Bei der Ermittlung der Emissionsfaktoren wurden die Messergebnisse bei Erdgas anhand der erfassten Jahresbetriebsstunden der jeweiligen Anlagen gewichtet, um die Emissionen der Anlagen mit höherer Laufzeit entsprechend stärker im Emissionsfaktor abzubilden. Bei Heizöl-Anlagen war eine Gewichtung nicht sinnvoll, da die Anlagen überwiegend mit Zweistoffbrennern ausgestattet waren und für Heizöl keine oder nur sehr geringe Betriebsstunden aufwiesen.

Tabelle 12 und Tabelle 13 dokumentieren die ermittelten Emissionskonzentrationen für bestehende Heizöl- und Erdgas-Feuerungsanlagen im Jahr 2020, d. h. für Anlagen, die bis zum 20. Dezember 2018 errichtet wurden. Die Darstellung erfolgt zur detaillierteren Berichterstattung gemäß Artikel 11 der EU-Richtlinie über mittelgroße Feuerungsanlagen (MCPD) getrennt nach den Leistungsklassen 1 MW bis unter 5 MW sowie 5 MW bis unter 10 MW.

Tabelle 12: Mittlere Emissionskonzentration für Kohlenmonoxid, Stickstoffoxide, Methan, NMVOC und Gesamtstaub für bestehende Heizöl-Anlagen mit 1 - < 10 MW im Jahr 2020

Nennwärme-leistung [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Staub [mg/Nm³]
1 - < 5	22	164	< 0,961	0,00	< 0,646
5 - < 10	34	150	< 1,16	0,00	< 1,00

Anmerkung: Wenn ein Wert mit "<" gekennzeichnet ist, lagen gemessene Werte unterhalb der Bestimmungsgrenze und sind mit halber Bestimmungsgrenze in die mittlere Emissionskonzentration eingeflossen. Es erfolgte keine Gewichtung nach Jahresbetriebsstunden, da ein Großteil der Heizöl-Anlagen keine oder nur sehr wenige Betriebsstunden aufwies.
Quelle: CO-Daten 2019 (UBA 2023a), übrige Daten eigene Messungen (2020-2022)

Tabelle 13: Mittlere Emissionskonzentration für Kohlenmonoxid, Stickstoffoxide, Methan, NMVOC und Gesamtstaub für bestehende Erdgas-Anlagen mit 1 - < 10 MW im Jahr 2020

Nennwärme-leistung [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Staub [mg/Nm³]
1 - < 5	19	117	< 1,15	0,00	< 0,207
5 - < 10	21	126	< 1,93	0,00	< 0,100

Anmerkung: Wenn ein Wert mit "<" gekennzeichnet ist, lagen gemessene Werte unterhalb der Bestimmungsgrenze und sind mit halber Bestimmungsgrenze in die mittlere Emissionskonzentration eingeflossen. Alle Werte außer für CO basieren auf eigenen Messdaten und wurden entsprechend der Jahresbetriebsstunden der gemessenen Anlagen gewichtet.
Quelle: CO-Daten 2019 (UBA 2023a), übrige Daten aus eigenen Messungen (2020-2022)

Für neue Heizöl- und Erdgas-Anlagen mit 1 MW bis unter 10 MW Nennwärmeleistung wurden mit Ausnahme von Stickstoffoxiden und Kohlenmonoxid die gleichen Werte angesetzt wie für bestehende Anlagen. Für die übrigen Schadstoffe (Gesamt-Kohlenstoff, NMVOC und Staub) ist nicht davon auszugehen, dass sich das Emissionsverhalten bei neuen Anlagen relevant verbessert bzw. verändert.

Für Kohlenmonoxid-Emissionen wurden die durchschnittlichen Emissionskonzentrationen aus der Berichterstattung Deutschlands an die EU zum 1. Januar 2021 gemäß MCPD Artikel 11 Absatz 2 verwendet. Grundlage für die Berechnungen waren Messungen des Landesinnungsverbands des Schornsteinfegerhandwerks in Bayern an 3.475 Erdgas- und 1.524 Heizöl-Feuerungen, zum anderen Emissionsmessungen an 490 genehmigungsbedürftigen mittelgroßen Feuerungsanlagen (321 Erdgas- und 169 Heizöl-Feuerungen). (UBA 2023a)

Für Stickstoffoxidemissionen aus neuen Heizöl-Anlagen wurde der an einer Anlage mit 3,2 MW und Baujahr 2018 gemessene Wert angesetzt. (Tabelle 14)

Tabelle 14: Mittlere Emissionskonzentrationen für Kohlenmonoxid, Stickstoffoxide, Methan, NMVOC und Gesamtstaub für neue Heizöl-Anlagen mit 1 - < 10 MW

Nennwärme-leistung [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Staub [mg/Nm³]
1 - < 5	21	92,9	< 0,961	0	< 0,646
5 - < 10	21	92,9	< 1,16	0	1,00

Anmerkung: Wenn ein Wert mit "<" gekennzeichnet ist, lagen gemessene Werte unterhalb der Bestimmungsgrenze und sind mit halber Bestimmungsgrenze in die mittlere Emissionskonzentration eingeflossen. Alle Werte außer für CO basieren

auf eigenen Messdaten. Es erfolgte keine Gewichtung nach Jahresbetriebsstunden, da ein Großteil der Heizöl-Anlagen keine oder nur sehr wenige Betriebsstunden aufwies. Nur der Emissionsfaktor für NOx basiert auf der Messung an einer neueren Anlage mit Inbetriebnahmejahr 2018. Die Werte für CH_4, NMVOC und Staub entsprechen den Emissionskonzentrationen für bestehende Anlagen, da für diese Parameter bei neueren Anlagen keine relevanten Änderungen angenommen werden.
Quelle: CO-Daten aus 2019 (UBA 2023a), übrige Daten aus eigenen Messungen (2020-2022)

Für Stickstoffoxidemissionen aus Erdgas-Anlagen werden zwei Szenarien berechnet: Szenario 1 verwendet für neue Anlagen den Mittelwert der Stickstoffoxid-Werte aus eigenen Messungen an fünf Neuanlagen mit 1 MW bis unter 5 MW (Inbetriebnahme 2019 bzw. 2020). (Tabelle 15)

Tabelle 15: Mittlere Emissionskonzentrationen für Kohlenmonoxid, Stickstoffoxide, Methan, NMVOC und Gesamtstaub für neue Erdgas-Anlagen mit 1 - < 10 MW, Szenario 1

Nennwärme-leistung [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mg C/Nm³]	Staub [mg/Nm³]
1 - < 5	19	78,9	< 1,15	0,00	< 0,207
5 - < 10	16	78,9	< 1,93	0,00	< 0,100

Anmerkung: Wenn ein Wert mit "<" gekennzeichnet ist, lagen gemessene Werte unterhalb der Bestimmungsgrenze und sind mit halber Bestimmungsgrenze in die mittlere Emissionskonzentration eingeflossen. Alle Werte außer für CO basieren auf eigenen Messdaten und wurden entsprechend der Jahresbetriebsstunden der gemessenen Anlagen gewichtet; nur die Werte für NOx basieren auf der Messung an fünf neueren Anlagen mit Inbetriebnahmejahren 2019 und 2020. Die Werte für CH_4, NMVOC und Staub entsprechen den Emissionskonzentrationen für bestehende Anlagen, da für diese Parameter bei neueren Anlagen keine relevanten Änderungen angenommen werden.
Quelle: CO-Daten aus 2019 (UBA 2023a), übrige Daten eigene Messungen (2020-2022)

Für Szenario 2 (Tabelle 16) wird angenommen, dass im Jahr 2030 in Deutschland in neuen und bestehenden Erdgasfeuerungsanlagen ein Grenzwert für Stickstoffoxide entsprechend der Vorgaben in den Niederlanden einzuhalten ist. Der NOx-Grenzwert in den Niederlanden beträgt für Erdgasanlagen mit 1 MW bis unter 10 MW Nennwärmeleistung 70 mg/Nm³, wobei die Messunsicherheit bei der Grenzwertüberprüfung abgezogen wird. Dies entspricht gemäß den Messdaten aus den Niederlanden (SCIOS 2022) in etwa der Festlegung eines NOx-Grenzwertes von 100 mg/Nm³, wenn zum Messwert die Messunsicherheit addiert wird, wie dies in Deutschland die 44. BImSchV zur Grenzwertüberprüfung vorgibt.

Tabelle 16: Mittlere Emissionskonzentrationen für Kohlenmonoxid, Stickstoffoxide, Methan, NMVOC und Gesamtstaub für Erdgas-Anlagen mit 1 - < 10 MW bei NOx-Grenzwertvorgabe wie in den Niederlanden

Nennwärme-leistung [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Staub [mg/Nm³]
1 - < 5	19	59,1	< 1,15	0,00	< 0,207
5 - < 10	16	59,1	< 1,93	0,00	< 0,100

Anmerkung: Wenn ein Wert mit "<" gekennzeichnet ist, lagen gemessene Werte unterhalb der Bestimmungsgrenze und sind mit halber Bestimmungsgrenze in die mittlere Emissionskonzentration eingeflossen. Die genutzten eigenen Messwerte (CH_4, NMVOC, Staub) wurden entsprechend der Jahresbetriebsstunden der gemessenen Anlagen gewichtet.
Quelle: CO-Daten aus 2019 (UBA 2023a), NOx-Daten 2017-2022 (SCIOS 2022), übrige Daten eigene Messungen 2020-2022

Zur Berechnung der Gesamtemissionen der Öl- und Gasfeuerungen mit 1 MW bis unter 10 MW Feuerungswärmeleistung wird der Energieverbrauch in den Anlagen benötigt, um eine „Aktivitätsrate“ mit dem Emissionsfaktor zu multiplizieren. Mangels anderweitiger Daten wurde dieser auf Basis der im Projekt erhobenen Energieverbräuche berechnet, die bei den 100 Messungen erhoben wurden. Der mittlere Brennstoffverbrauch pro installierter Leistung der gemessenen Anlagen [MJ/MW] wurde anhand der Daten des Schornsteinfegerverbandes zum Gesamtbestand in Deutschland hochgerechnet (ZIV 2019).

Für das Jahr 2020 ergibt sich ein Energieverbrauch von 266.123 TJ Heizöl und Erdgas in Anlagen mit 1 MW bis unter 10 MW Nennwärmeleistung in Deutschland. Der Gasverbrauch hat darin einen Anteil von 99,4 %, der Heizölverbrauch einen Anteil von 0,6 %.

Die Prognose ergibt für das Jahr 2030 im Vergleich mit dem Jahr 2020 einen 10,9 % geringeren Energieverbrauch von 237.013 TJ Heizöl und Erdgas in Anlagen mit 1 MW bis unter 10 MW Nennwärmeleistung. Der Gasverbrauch hat dabei einen Anteil von 99,4 % und der Heizölverbrauch einen Anteil von 0,6 %. Für den Energieverbrauch im Jahr 2030 erfolgte entsprechend dem im Auftrag des Umweltbundesamtes erstellten „Projektionsbericht 2021“ (Repenning et al. 2021) die Annahme, dass der Verbrauch bei Heizöl gegenüber dem Jahr 2020 unverändert bleibt und der Verbrauch bei Erdgas von 2020 bis 2030 um 11 % abnimmt.

Die ermittelten Emissionskonzentrationen [mg/Nm³] wurden mit dem Faktor 0,28 zu Emissionsfaktoren [kg/TJ] umgerechnet und mit den Energieverbräuchen multipliziert, um die Gesamtemissionen zu erhalten. Dabei erfolgte in den Berechnungen für die Jahre 2020 und 2030 eine Berücksichtigung des Anteils an Neuanlagen. Für Neuanlagen wurde bei CO- und NOx-Emissionen ein geringerer Emissionsfaktor als für bestehende Anlagen angesetzt.

Die Daten des ZIV (2019) zeigen, dass in den Jahren 2015 bis 2019 bezogen auf den Gesamtbestand im Mittel jährlich etwa 2 % Heizöl- und 3 % Erdgasanlagen erneuert wurden. Daher wurde für das Jahr 2020 angenommen, dass die in den Jahren 2019 und 2020 errichteten Neuanlagen etwa 4 % der Heizöl- und 6 % der Erdgasanlagen ausmachen. Für das Jahr 2030 wurde entsprechend angenommen, dass Neuanlagen, die in den Jahren 2019 bis 2030 errichtet wurden, 24 % der Heizöl- und 36 % der Erdgasanlagen ausmachen.

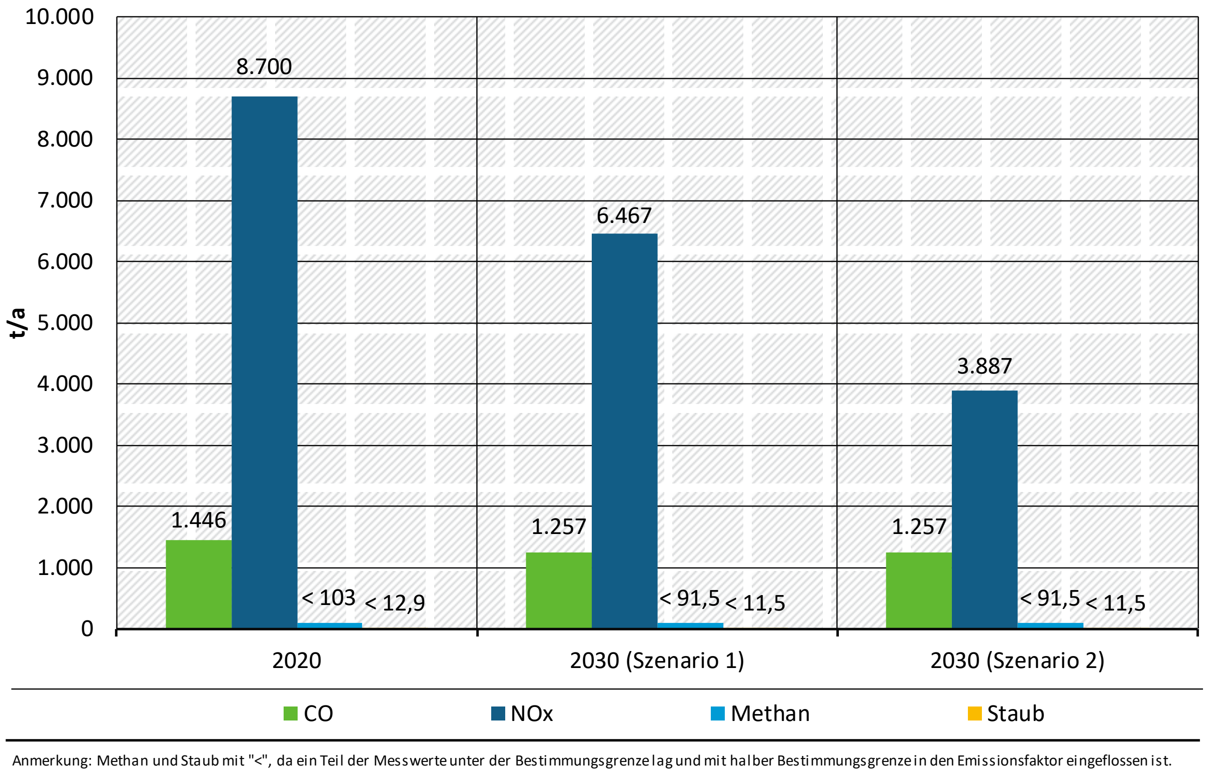
Abbildung 10 zeigt die berechneten Emissionen aus Erdgasanlagen mit 1 MW bis unter 10 MW Nennwärmeleistung in Deutschland in den Jahren 2020 bis 2030. Für 2030 zeigt das Szenario 1 die berechnete Entwicklung ohne Grenzwertveränderung, das Szenario 2 die Entwicklung bei der Vorgabe eines Grenzwertes von 100 mg/Nm³ anstelle von 150 mg/Nm³, der unter Aufschlag der Messunsicherheit einzuhalten ist.

Die Emissionen für Stickstoffoxide aus Erdgasfeuerungen lagen im Jahr 2020 bei rund 8.700 Tonnen. Für das Jahr 2030 ist eine Senkung auf rund 6.500 Tonnen zu erwarten (-25 %); würde ein Grenzwert wie in den Niederlanden festgelegt, würden die Stickstoffoxide-Emissionen auf rund 3.900 Tonnen im Jahr 2030 sinken (-55 %).

Für 2020 ergaben sich zudem aus Erdgasfeuerungen Emissionen von weniger als 13 Tonnen Staub (<12 Tonnen in 2030), weniger als 103 Tonnen Methan (<92 Tonnen in 2030), rund 1.400 Tonnen Kohlenmonoxid (1.300 Tonnen in 2030) und keine NMVOC-Emissionen.

Für Heizöl-Feuerungen resultierten für 2020 und 2030 Emissionen von rund 65 Tonnen Stickstoffoxiden, rund 10 Tonnen Kohlenmonoxid, jeweils weniger als 0,5 Tonnen Methan und Staub sowie keine NMVOC-Emissionen.

Abbildung 10: Entwicklung der Emissionen aus Erdgasfeuerungen mit 1 MW bis unter 10 MW Nennwärmeleistung in Deutschland zwischen 2020 und 2030



Quelle: eigene Darstellung (Ökopol)

Zusätzlich zur Emissionsberechnung erfolgten Recherchen zu besten verfügbaren Techniken in öl- und gasgefeuerten Anlagen mit 1 MW bis unter 10 MW Nennwärmeleistung. Dazu wurden Interviews mit Herstellern, Verbänden und Behörden sowie ein Fachgespräch durchgeführt.

In Tabelle 17 sind die Emissionsminderungstechniken aufgeführt, die von den Betreibern zu den gemessenen Anlagen im Fragebogen berichtet wurden. Die Vollständigkeit der Angaben hing von der Kenntnis der zuständigen Kontaktperson ab. Durch Unterstützung der Hersteller bei der Analyse von Brennertypen anhand der Fotos von Typenschildern konnten zusätzliche Brenner mit NO_x-Minderungstechnik identifiziert werden, die von den Betreibern nicht angegeben wurden (BDH 2022). Es besteht die Möglichkeit, dass weitere Betreiberangaben zu Emissionsminderungstechniken unvollständig sind, da nicht alle Brenner-Typenschilder zugänglich für die Erstellung von Fotos waren oder von Herstellern waren, die sich nicht an der Typenschild-Analyse beteiligt haben.

Bei 100 Messungen in 79 Anlagen wurde bei 27 Anlagen der Einsatz von Low NO_x-Brennern zur Stickstoffoxid-Minderung dokumentiert (34 %). Etwa ein Viertel dieser Low NO_x-Brenner wurden in bestehenden Anlagen nachgerüstet. Bei sechs der 27 Anlagen wurde angegeben, dass sie über Low NO_x-Brenner und eine Abgasrückführung zur Stickstoffoxid-Minderung verfügen.

Von insgesamt 28 Anlagen mit Heizölfeuerung, an denen eine Messung erfolgte, wurde bei zehn Anlagen (36 %) angegeben, dass schwefelarmes Heizöl zum Einsatz kam. Dabei ist zu berücksichtigen, dass sieben der zehn Anlagen Mehrstoffbrenner nutzen, die bis 2021 überwiegend mit Gas betrieben wurden und somit eher ältere Heizöl-Lagerbestände aufwiesen.

Lambda-Sonden bzw. O_2-Regelungen, die einen besseren Ausbrand und somit geringere Emissionen von CO, Methan und Gesamt-Kohlenstoff bewirken, wurden bei neun der 79 Anlagen dokumentiert (11 %). Eine Abwärmenutzung, die zu spezifisch geringeren Gesamtemissionen führt, wurde von den Betreibern bei 19 der 79 Anlagen angegeben (24 %).

Eine Kombination der Techniken wurde selten genannt: Zwei Anlagen verfügen über Low NO_x-Brenner und eine O_2-Regelung.

Tabelle 17: Informationen zu Emissionsminderungstechniken an den gemessenen Anlagen

Emissions-minderungs-technik	Zweck der Technik	Einbau bei Instal-lation	Einbau als Nach-rüstung	Bestehende Anlagen (vor 20.12.2018)	Neu-anlagen (ab 20.12.2018)	Mehrstoff-feuerungs-anlagen
Low NO_x-Brenner	Minderung von Stickstoffoxiden	21	6	24	3	4
Abgasrück-führung	Minderung von Stickstoffoxiden, Ausbrand verbessert	1	5	6	0	1
Schwefelarmes Heizöl	Minderung von Schwefeldioxiden	-	-	10	0	7
Lambda-Sonde / O_2-Regelung	Verbesserung der Brennstoffnutzung und des Ausbrandes, dadurch Minderung von CO, Methan und NMVOC	7	2	9	0	1
Abgaswärme-nutzung / Wärmetauscher	Verbesserung der Brennstoffnutzung, dadurch geringere spezifische Emissionen	k. A.	k. A.	19	4	2

Quelle: Betreiberfragebogen von 79 Anlagen (eigene Erhebung), Herstellerangaben zu 21 Brennern (BDH 2022)

Weiterhin wurden in mehreren europäischen Ländern Recherchen zur Grenzwertsetzung durchgeführt, insbesondere zu divergierenden Messanforderungen und Bewertungssystemen für die Messwerte bei der Überprüfung der Einhaltung von Grenzwerten.

Tabelle 18 gibt eine Übersicht über die jeweiligen Grenzwert- und Messanforderungen der mittelgroßen Feuerungsanlagen in sechs ausgewählten europäischen Ländern.

Die Angaben in der Tabelle verdeutlichen, dass die Grenzwerte und Messanforderungen der betrachteten Länder deutlich voneinander abweichen. Dies betrifft auch die zu messenden Parameter. Flandern verlangt bei Erdgasfeuerungen auch die Einhaltung von Grenzwerten für Schwefeldioxide und Staub. Zusätzlich zu CO, NO_x, Staub oder der Rußzahl verlangt Flandern bei der Feuerung mit flüssigen Brennstoffen auch die Einhaltung von Grenzwerten für zwei Schwermetalle (Vanadium und Nickel).

Weiterhin besteht ein großer Unterschied in der Bewertung der Messergebnisse. Zum einen ist die Messunsicherheit unterschiedlich zu behandeln. In Österreich und den Niederlanden beispielsweise ist die Messunsicherheit zu subtrahieren, in Deutschland und Flandern zu addieren. Zum anderen kann in manchen Ländern der Mittelwert der Messungen mit dem Grenzwert verglichen werden, in anderen Ländern muss jeder Messwert den Grenzwert einhalten. Auch die vorgegebenen Messperioden unterscheiden sich zwischen viertel-, ein-, zwei- und dreijährig.

Tabelle 18: Anforderungen an mittelgroße Feuerungsanlagen in Flandern/Belgien, Dänemark, Schweiz, Österreich, Deutschland und den Niederlanden

	Flandern (1-20 MW)	DK (< 10 MW)	CH (< 10 MW)	AT (1-20 MW)	DE (1-10 MW)	NL (1-20 MW)
Grenzwerte Erdgas 1) [mg/Nm3]	NOx: 80-300 CO: 100-250 SO_2: 35 Staub: 5-50	NOx: 100-105 CO: 125	NOx: 80 CO: 100 NH_3: 30	NOx: 100-120 CO: 80	NOx: 100-150 CO: 80-110	NOx: 70
Grenzwerte Heizöl 2) [mg/Nm³]	NOx: 185-650 CO: 175-250 SO_2: 170-1700 Staub: 5-200 Nickel: 3 Vanadium: 5	NOx: 180 CO: 165	NOx: 80 CO: 100 NH_3: 30 Rußzahl: 1	NOx: 150 CO: 80 Staub: 10-20	NOx: 200 CO: 80-150 Rußzahl: 1	NOx: 120 SO_2: 200 Staub: 5
Anforderung bezüglich der Messunsicherheit	Addition	Keine Berück-sichtigung	Subtraktion	Subtraktion	Addition	Subtraktion
Messunsicherheit max.	Alle Parameter: 30 %	-	-	NOx: 20 % CO: 10 % Staub: 30 %	-	NOx: 20 % SO_2: 20 % Staub: 30 %
Messdauer	Eine Messung (60 min. oder 90 min.)	2 x 45 Minuten	3 x 30 Minuten	3 x 30 Minuten	3 x 30 Minuten	3 x 30 Minuten
Grenzwert-Abgleich	Mittel der Einzelwerte	Mittel der Einzelwerte	Mittel der Einzelwerte	Jeder Einzelwert	Jeder Einzelwert	Jeder Einzelwert
Messzyklen (nur Anlagen > 500 Jahres-betriebsstunden)	Alle 2 Jahre für 1 - < 5 MW Alle 3 Monate für 5 - < 20 MW	Alle 2 Jahre für < 5 MW Einmal pro Jahr für 5 - < 10 MW und > 3000 Stunden/a	Alle 2 Jahre	Alle 3 Jahre	Alle 3 Jahre	Alle 3 Jahre für Neu-anlagen, einmalig für bestehende Anlagen (alle 3 Jahre ab 2025 für ≥ 5 MW, ab 2030 für 1 - 5 MW)

Quelle: UBA-Workshop (2022)

[2] Emissionsgrenzwerte hängen von der Anlagenkapazität, den Betriebsstunden und dem Datum der ersten Genehmigung ab.

1 Background and objectives of the project

Before 18 December 2015, medium oil and gas firing plants with a nominal heat output of 1 - 10 MW that did not require a permit were subject to the requirements of the "Ordinance on Small and Medium Combustion Plants" (1st BImSchV 2010) in Germany. Since then, they have fallen under the scope of the "EU Directive 2015/2193 on the limitation of emissions of certain pollutants into the air from medium combustion plants" (EU Directive 2015). The directive was transposed into national law in Germany by the "Ordinance on Medium Combustion, Gas Turbine and Internal Combustion Engine Plants" (44th BImSchV 2019).

According to EU Directive 2016/2284, Germany must reduce NO_x emissions by 65 % and SO_2 emissions by 58 % by 2030 compared to 2005 for all sources (EU "NEC" Directive 2016). Medium combustion plants are a relevant source of emissions, particularly for emissions of nitrogen oxides.

The aim of the research project was to estimate the emissions from medium oil and gas combustion plants and to calculate a forecast of emissions from these systems for the year 2030 (for results see chapter 2). To this end, 100 measurements of key air pollutants were to be carried out (for results, see Chapter 3). The aim of the measurements was to determine emission factors that are representative of the total stock of medium oil and gas combustion plants with a rated thermal input of 1 MW to less than 10 MW in Germany.

Furthermore, the aim of the research project was to research the best available techniques for oil and gas-fired combustion plants with a rated thermal input of 1 MW to less than 10 MW (for results see chapter 4). To this end, literature research, interviews with companies and the authorities of several Member States were to be carried out and a workshop on the subject organised. At the workshop, companies that manufacture burner and emission reduction techniques should present and discuss their systems with the associated advantages and disadvantages as well as the framework conditions required for low emissions.

Finally, the aim of the project was to compare the legal framework conditions for medium combustion plants in selected countries (for results see chapter 5). To this end, research was to be carried out in six European countries that were assumed to have set ambitious emission limits. The differences in the limit value settings were to be analysed in more detail, particularly against the background of slightly different measurement requirements and evaluation systems for the measured values. The authorities of the six countries were to be given the opportunity to present and discuss the regulatory requirements at a workshop in which manufacturers of combustion plants and their association BDH also took part.

2 Emissions from medium fuel oil and natural gas combustion plants with 1 MW to less than 10 MW in 2020 and 2030

This chapter calculates the emissions of nitrogen oxides, dust, TOC, carbon monoxide, methane and NMVOCs from fuel oil and natural gas combustion plants with a rated thermal input of 1 MW to less than 10 MW in Germany for the years 2020 and 2030.

Chapter 2.1 explains the basis for the calculations. Chapter 2.2 presents the existing systems, Chapter 2.3 the nominal heat output of the existing systems . Chapters 2.4 and 2.5 calculate the energy consumption for 2020 and 2030. Chapters 2.6 to 2.9 determine emission factors from average emission concentrations. Chapters 2.10 and 2.11 calculate the emissions resulting from energy consumption and emission factors. Chapter 2.12 graphically shows the development of emissions in 2020 and 2030.

2.1 Basis of calculation

Emissions are calculated in accordance with the guidelines of the European Measurement and Evaluation Programme and the European Environment Agency (EMEP/EEA 2019) on the basis of "activity rates" and "emission factors".

- Activity rates quantify the energy input of the plants in the reference year [TJ/a],
- Emission factors quantify the mass of emissions per energy input [mg/MJ].

The **activity rates** for the reference years 2020 and 2030 are based on the following data:

- Survey by the Federal Association of Chimney Sweeps in 16 federal state guilds on the stock of medium natural gas and fuel oil combustion plants in Germany with a nominal heat output of 1 MW to less than 10 MW in 2019 (ZIV 2020).
- Survey of annual energy consumption in the medium natural gas and fuel oil plants with 1 MW to less than 10 MW nominal heat output measured as part of the project.
- Assumptions for the lower calorific value: natural gas H with 36.7 MJ/m^3, fuel oil L with 42.816 MJ/kg and for the density of fuel oil 0.85 kg/l (UBA 2022)
- Assumption of a conversion factor of 0.28 for mg/Nm^3 in mg/MJ for emissions from fuel oil and natural gas combustion plants (UBA 2023b)
- Assumptions on the change in fuel oil and natural gas consumption between 2020 and 2030: for fuel oil 0 % and for natural gas reduction of 11 % from 2020 to 2030, both based on the 2021 projection report for Germany (Repenning et al. 2021), consolidated by a trend survey on new heating systems with 1 MW to less than 10 MW as part of the project (Enercity 2023, vedec 2023).

The **emission factors** used as basis for emission estimates for 2020 and 2030 are based on

- 100 measurements of emissions of nitrogen oxides, dust, TOC and methane that were carried out in Germany on medium natural gas and fuel oil plants with a nominal heat output of 1 MW to less than 10 MW between November 2020 and April 2022 as part of the project.

NMVOC emissions were calculated from the measurement results for TOC and methane. Average emission concentrations were determined for all measured parameters, weighted according to the operating hours of the systems.

- Average emission concentrations of carbon monoxide that Germany reported to the EU on 1 January 2021 in accordance with Article 11 (2) of the MCPD. The reporting was based on 5,489 measurements of emissions from medium combustion plants with a nominal heat output of 1 MW to less than 20 MW in 2019, which were carried out by the State Association of Chimney Sweeps in Bavaria on 3,475 natural gas and 1,524 fuel oil combustion plants, and also originate from databases of the federal states from measurements on 490 combustion plants subject to permitting (321 natural gas and 169 fuel oil combustion plants) (UBA 2023a).
- 1,656 measurements of nitrogen oxides emissions carried out in the Netherlands on medium natural gas combustion plants with a rated thermal input of 1 MW to less than 10 MW in 2020, 2021 and 2022. There, 70 mg/Nm^3 must be complied with as the NOx limit value, after deducting the measurement uncertainty from the measured value (SCIOS 2022).
- Assumption that the emissions from plants with a nominal heat output of 1 MW to less than 10 MW, the number of which is recorded in the ZIV statistics, roughly correspond to the emissions from plants with a rated thermal input of 1 MW to less than 10 MW, which are subject to the MCPD and for which no statistics are available.[3]
- The nominal heat output of the existing plants in Germany according to the ZIV statistics is set in relation to the nominal heat output of the measured plants. This factor is used to extrapolate the fuel consumption recorded in the measured plants to the fuel consumption of all plants in Germany.

2.2 Total number of plants

The number of oil and gas combustion plants with a nominal heat output of 1 MW to less than 10 MW that do not require a permit is surveyed by the Federal Association of Chimney Sweeps (ZIV). The survey in the 16 state guild associations is carried out by means of questionnaires to the individual sweeping districts; missing responses from districts are extrapolated by the federal association for the total number.

The statistics are grouped according to the nominal heat output of the plant and the date of commissioning.

A survey by the Federal Association of Chimney Sweeps (ZIV) documents the number of plants in 2019 (ZIV 2020).

Table 19 shows the number of gas combustion plants, Table 20 the number of oil combustion plants, each grouped by nominal heat output class and commissioning period. The total number of installed natural gas and fuel oil combustion plants in 2019 was 12,593.

[3] As the rated thermal input of a plant without waste gas condensation is higher than the nominal heat output (the difference originates mainly from flue gas losses and boiler losses), plants with a rated thermal input of around 1 MW to 1.1 MW are missing in the lower range of the ZIV statistics, as the nominal heat output is less than 1 MW. In the upper range, on the other hand, the ZIV statistics include plants with a nominal heat output of around 9 MW to 9.9 MW, which have a rated thermal input of 10 MW or more.

Table 19: Gas-fired plants with 1 - < 10 MW nominal heat output by commissioning and nominal heat output (2019)

Commissioning	1 - < 2 MW	2 - < 3 MW	3 - < 4 MW	4 - < 5 MW	5 - < 10 MW	Total
before 01.01.1970	38	40	37	27	53	**195**
01.01.1970 to 31.12.1974	85	44	25	15	48	**217**
01.01.1975 to 31.12.1979	119	47	24	15	52	**257**
01.01.1980 to 31.12.1984	165	66	24	11	49	**315**
01.01.1955 until 31.12.1989	365	118	45	61	82	**671**
01.01.1990 to 31.12.1994	707	221	138	66	199	**1331**
01.01.1995 until 31.12.1999	708	220	90	102	111	**1231**
01.01.2000 until 31.12.2004	837	321	89	64	119	**1430**
01.01.2005 until 31.12.2009	674	209	74	24	107	**1088**
01.01.2010 until 31.12.2014	814	308	88	58	103	**1371**
01.01.2015 until 31.12.2019	798	282	84	51	95	**1310**
Total	**5310**	**1876**	**718**	**494**	**1018**	**9416**

Source: ZIV (2020)

Table 20: Oil-fired plants with 1 - < 10 MW nominal heat output by commissioning and nominal heat output (2019)

Commissioning	1 - < 2 MW	2 - < 3 MW	3 - < 4 MW	4 - < 5 MW	5 - < 10 MW	Total
before 01.01.1970	50	12	14	5	13	**94**
01.01.1970 to 31.12.1974	59	14	9	10	16	**108**
01.01.1975 to 31.12.1979	50	23	7	8	11	**99**
01.01.1980 to 31.12.1984	75	23	7	5	11	**121**
01.01.1955 until 31.12.1989	174	35	16	40	31	**296**
01.01.1990 to 31.12.1994	285	90	46	18	56	**495**
01.01.1995 until 31.12.1999	276	69	30	20	23	**418**
01.01.2000 until 31.12.2004	280	132	29	9	32	**482**
01.01.2005 until 31.12.2009	255	91	40	7	29	**422**
01.01.2010 until 31.12.2014	211	83	21	14	20	**349**
01.01.2015 until 31.12.2019	189	63	18	9	14	**293**
Total	**1904**	**635**	**237**	**145**	**256**	**3177**

Source: ZIV (2020)

2.3 Nominal heat output of existing plants

To calculate the energy consumption of all oil and gas combustion plants with 1 MW to less than 10 MW, an average nominal heat output is assumed for each of the output classes of the Federal Association of Chimney Sweeps (ZIV 2020) and multiplied by the number of installed plants in the output class.

Table 21 shows the installed nominal heat output of the oil-fired boilers, Table 22 shows the installed nominal heat output of gas combustion plants.

Table 21: Installed nominal heat output of oil-fired boilers with 1 - < 10 MW (2019)

Oil combustion plants	1 - < 2 MW	2 - < 3 MW	3 - < 4 MW	4 - < 5 MW	5 - < 10 MW	Total
Number of plants	1904	635	237	145	256	**3177**
Average nominal heat output	1.5	2.5	3.5	4.5	7.5	
Nominal heat output	2856	1588	830	653	1920	**7847**
Share	36.4 %	20.2 %	10.6 %	8.3 %	24.5 %	**100 %**

Source: Ökopol based on ZIV (2020)

Table 22: Installed nominal heat output of gas-fired boilers with 1 - < 10 MW (2019)

Gas combustion plants	1 - < 2 MW	2 - < 3 MW	3 - < 4 MW	4 - < 5 MW	5 - < 10 MW	Total
Number of plants	5310	1876	718	494	1018	**9416**
Average nominal heat output	1.5	2.5	3.5	4.5	7.5	
Nominal heat output	7965	4690	2513	2223	7635	**25026**
Share	31.8 %	18.7 %	10.0 %	8.9 %	30.5 %	**100 %**

Source: Ökopol based on ZIV (2020)

2.4 Energy consumption of fuel oil and natural gas in plants with 1 MW to less than 10 MW nominal heat output in 2020

Table 23 and Table 24 calculate the energy consumption in 2020 for fuel oil and natural gas combustion plants in Germany with a nominal heat output of 1 MW to less than 10 MW that do not require permits, assuming that the number of plants in 2020 corresponded to the number recorded in a survey conducted by the Federal Association of Chimney Sweeps in 2019 (ZIV 2019).

Operating hours and fuel consumption were recorded for 100 measurements carried out in the project on 79 fuel oil and natural gas combustion plants with a nominal heat output of 1 MW to less than 10 MW. No data on annual energy consumption was provided for eight gas combustion plants, and no fuel oil was consumed in three multi-fuel combustion plants. A plausibility check was carried out on the data for the remaining plants. For one plant with multi-fuel burner and one plant with fuel oil burner as well as for nine plants with natural gas burners, it was found that either the operating hours or the fuel consumption were incorrect (the documented energy consumption may include other plants at the site). The stated energy consumption was significantly higher than the energy consumption that results when the plant is in operation at full load with the stated operating hours.

In the survey conducted by the Chimney Sweep Association (ZIV 2019), multi-fuel combustion plants designed for oil and gas operation were allocated to the fuel that was predominantly used in the survey year. Therefore, when calculating the specific consumption of fuel oil plants, only the three multi-fuel combustion plants that were operated exclusively with fuel oil were taken into account in addition to the single-fuel combustion plants. All other mixed combustion plants were predominantly operated with natural gas and were therefore allocated to these.

This made it possible to calculate specific energy consumption values per installed megawatt of nominal heat output from 60 plants and use them to extrapolate the energy consumption of the total number of plants in Germany. Table 23 and Table 24 show the results for fuel oil and natural gas energy consumption in plants with 1 MW to less than 10 MW nominal heat output in 2020.

Table 23: Energy consumption of fuel oil in plants with 1 - < 10 MW nominal heat output in 2020

Nominal heat output range [MW]	Single-fuel / multi-fuel fuel oil plants measured	Nominal heat output of measured plants [MW]	Fuel oil consumption measured plants [l/a]	Specific consumption of measured plants [MJ/(MW*a)]	Installed nominal heat output of all plants [MW]	Fuel oil consump-tion all plants [TJ/a]
1 - < 10	**9**	**34,19**	**177.302**	**188.729**	**7.847**	**1.481**

Assumptions: Average calorific value of fuel oil L 42.816 MJ/kg (UBA 2022), density 0.85 kg/l

Source: Energy consumption from own survey (2020/2021); installed nominal heat output based on ZIV (2019)

Table 24: Energy consumption of natural gas in plants with 1 - < 10 MW nominal heat output in 2020

Nominal heat output range [MW]	Single-fuel/multi-fuel natural gas plants measured	Nominal heat output of measured plants [MW]	Natural gas consumptio n of measured plants [m^3 /a]	Specific consumption of measured plants [MJ/(MW*a)]	Installed nominal heat output of all plants [MW]	Natural gas consumpti on all plants [TJ/a]
1 - < 10	**51**	**83.90**	**24 174 782**	**10.572.110**	**25 026**	**264.578**

Assumption: Average calorific value of natural gas H 36.7 MJ/m^3 (UBA 2022)

Source: Energy consumption from own survey (2020/2021); installed nominal heat output based on ZIV (2019)

Table 25 shows the total energy consumption of oil and gas combustion plants (266 123 TJ) and broken down into the output classes 1 - < 5 MW and 5 - < 10 MW nominal heat output. It is based on the nominal heat output of the output classes. In 2020, fuel oil consumption accounted for 0.6 % of the total energy consumption of fuel oil and natural gas combustion plants, while natural gas consumption accounted for 99.4 %.

Table 25: Energy consumption of fuel oil and natural gas in plants with 1 - < 5 MW and 5 - < 10 MW nominal heat output in 2020

Nominal heat output range	Oil 1 - < 5 MW	Oil 5 - < 10 MW	Gas 1 - < 5 MW	Gas 5 - < 10 MW	Total
Number of plants	2 921	256	8 398	1 018	**12 593**
Nominal heat output [MW]	5 927	1 920	17 391	7 635	**32 873**
Share of nominal heat output	18 %	6 %	53 %	23 %	**100 %**
Specific energy consumption [GJ/(MW*a)]	201	201	10 575	10 575	
Energy consumption [TJ/a]	**1 119**	**362**	**183 904**	**80 738**	**266 123**

Source: Ökopol based on ZIV (2020)

2.5 Energy consumption of fuel oil and natural gas in plants with 1 MW to less than 10 MW nominal heat output in 2030

Table 26 and Table 27 calculate the projected energy consumption for fuel oil and natural gas in plants in Germany not requiring a permit with a nominal heat output of 1 MW to less than 10 MW in 2030, assuming that, according to the estimate in the 2021 projection report, the energy consumption of these plants will not change compared to 2020 for fuel oil and will decrease by 13 % for natural gas from 2018 to 2030[4], i.e. by around 11 % from 2020 to 2030 (Repenning et al. 2021). The 11 % reduction is roughly in the middle of the scenarios of a study by the Institute of Energy Economics in Cologne on future gas demand in Europe: the institute assumes on the one hand that consumption will remain unchanged and on the other hand that it will fall by 20 % (Çam et al. 2022).

As part of the project, a trend survey was conducted on new medium combustion plants with 1 MW to less than 10 MW, which revealed that new plants generally comprise a combination of combined heat and power plants, biomass or geothermal plants and natural gas boilers for peak loads (Enercity 2023, vedec 2023). A reduction of 11 % from 2020 to 2030 was considered a realistic possibility by the interviewees, as new plants reduce gas consumption by increasing efficiency (condensing boilers) and new plants only require natural gas at peak load times when combined with renewable energies.

In addition to a few plants with single-fuel fuel oil burners, natural gas was predominantly used in mono-fuel or dual-fuel burners in 2020/2021. Due to the trend reported by manufacturers in 2021/2022 towards converting plants from single-fuel natural gas burners to dual-fuel burners, a slight increase in fuel oil consumption can be expected if there is a relevant price difference, which could be offset by the decommissioning of obsolete fuel oil plants. In comparison with 2020, a constant fuel oil energy consumption is therefore assumed for 2030, in line with the assumptions in the 2021 projection report (Repenning et al. 2021).

[4] Reduction in "energy use in the rest of the energy industry (excluding power plants) in the "with measures" scenario" 2018 to 2030: 84 PJ -> 73 PJ

Table 26: Energy consumption of fuel oil plants with 1 - < 10 MW nominal heat output in 2030

Nominal heat output [MW]	Energy consumption of the plants in DE in 2020 [TJ/a]	Change in consumption	Energy consumption of plants in DE in 2030 [TJ/a]
1 - < 5	1 119	0 %	1 119
5 - < 10	362	0 %	362
1 - < 10	**1 481**	**0 %**	**1 481**

Source: Ökopol based on ZIV (2020), own surveys and Repenning et al. (2021)

Table 27: Energy consumption of natural gas plants with 1 - < 10 MW nominal heat output in 2030

Nominal heat output [MW]	Energy consumption of the plants in DE in 2020 [TJ/a]	Change in consumption	Energy consumption of plants in DE in 2030 [TJ/a]
1 - < 5	183 904	-11 %	163 675
5 - < 10	80 738	-11 %	71 857
1 - < 10	**264 642**	**-11 %**	**235 532**

Source: Ökopol based on ZIV (2020), own surveys and Repenning et al. (2021)

In total, the forecast for 2030 shows a 10.9 % reduction in energy consumption compared to 2020 of 237,013 TJ of fuel oil and natural gas in plants with a nominal heat output of 1 MW to less than 10 MW. Gas consumption accounts for 99.4 %, fuel oil consumption for 0.6 %.

2.6 Emission factors of existing fuel oil and natural gas plants with 1 MW to less than 10 MW nominal heat output in 2020

The average emission concentrations documented in this chapter are based on 100 measurements carried out by the project between 2020 and 2022 on medium fuel oil and natural gas combustion plants in Germany with a nominal heat output of 1 MW to less than 10 MW. Nitrogen oxides (NOx), methane (CH_4), total organic carbon and total dust were measured (see chapter 2.12). Specific emission factors per energy input [mg/MJ] are calculated from the emission concentrations [mg/Nm³].

The average emission concentrations for carbon monoxide were taken from the data already available at the German Environment Agency from Germany's reporting to the EU in accordance with Article 11(2) of the EU Directive (2015) on medium combustion plants for plants with a rated thermal input of 1 MW to less than 20 MW, as they were considered to be more representative than the company's own measurements due to the high number. On the one hand, the data set consists of measurements taken by the Bavarian State Association of Chimney Sweeps on plants that do not require a permit and, on the other hand, measurements from plants registered with the state authorities that require a permit. (UBA 2023a)

Table 28 and Table 29 document the average emission concentrations determined for existing fuel oil and natural gas combustion plants in 2020, i.e. for plants that were built before 20

December 2018. For more detailed reporting in accordance with Article 11 of the MCPD (EU Directive 2015), the description is broken down into the capacity classes 1 MW to less than 5 MW and 5 MW to less than 10 MW.

The data from own measurements are based on three consecutive measurements, each of which generally lasted 30 minutes and from which an average value was calculated. If values below the limit of quantification were obtained, the values were included in the emission factor with half the limit of quantification and the factor was labelled with a "<" in front.

The NMVOC emissions were determined by subtracting the carbon portion of the methane measurement value from the TOC measurement value. This resulted in emission concentrations for NMVOCs that totalled 0 mg C/Nm³ in all size classes.

When determining the emission concentrations, the measurement results for natural gas were weighted according to the recorded annual operating hours of the respective plants in order to reflect the emissions of the plants with longer operating times more strongly in the average emission concentration. Weighting did not make sense for fuel oil plants, as the plants were predominantly equipped with dual-fuel burners and fuel oil plants had no or very few operating hours.

Table 28: Average emission concentration at 3 % O_2 for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for existing fuel oil plants with 1 - < 10 MW in 2020

Nominal heat output [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	22	164	< 0.961	0.00	< 0.646
5 - < 10	34	150	< 1.16	0.00	< 1.00

Note: If a value is labelled "<", the measured values were below the limit of quantification and were included in the average emission concentration with half the limit of quantification. No weighting was carried out according to annual operating hours, as the majority of the fuel oil plants had no or very few operating hours.
Source: CO data 2019 (UBA 2023a), other data own measurements (2020-2022)

Table 29: Mean emission concentration at 3 % O_2 for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for existing natural gas plants with 1 - < 10 MW in 2020

Nominal heat output [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	19	117	< 1.15	0.00	< 0.207
5 - < 10	21	126	< 1.93	0.00	< 0.100

Note: If a value is labelled "<", the measured values were below the limit of quantification and have been included in the average emission concentration with half the limit of quantification. All values except for CO are based on own measurement data and were weighted according to the annual operating hours of the measured plants.
Source: CO data 2019 (UBA 2023a), other data from own measurements (2020-2022)

Table 30 and Table 31 document the resulting emission factors [mg/MJ] for existing fuel oil and natural gas plants if a conversion factor of 0.28 is applied to the average emission concentrations [mg/Nm³] (UBA 2023b).

Table 30: Emission factors for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for existing fuel oil plants with 1 - < 10 MW in 2020

Nominal heat output [MW]	CO [mg/MJ]	NOx [mg/MJ]	CH_4 [mg/MJ]	NMVOC [mgC/MJ]	Dust [mg/MJ]
1 - < 5	6.16	45.9	< 0.269	0	< 0.181
5 - < 10	9.52	42.0	< 0.325	0	< 0.280

Note: If a value is labelled "<", the measured values were below the limit of quantification and are included in the emission factor with half the limit of quantification. Conversion factor [mg/Nm³] to [mg/MJ]: 0.28.
Source: CO values based on 2019 (UBA 2023a), other data based on own measurements (2020-2022)

Table 31: Emission factors for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for existing natural gas plants with 1 - < 10 MW in 2020

Nominal heat output [MW]	CO [mg/MJ]	NOx [mg/MJ]	CH_4 [mg/MJ]	NMVOC [mgC/MJ]	Dust [mg/MJ]
1 - < 5	5.32	32.8	< 0.322	0	< 0.0580
5 - < 10	5.88	35.3	< 0.540	0	< 0.0280

Note: If a value is labelled "<", the measured values were below the limit of quantification and are included in the emission factor with half the limit of quantification. Conversion factor [mg/Nm³] to [mg/MJ]: 0.28.
Source: CO values based on 2019 (UBA 2023a), other data based on own measurements (2020-2022)

2.7 Emission factors of existing fuel oil and natural gas plants with 1 MW to less than 10 MW nominal heat output in 2030 in Germany

The average emission concentrations of existing fuel oil and natural gas plants with 1 MW to less than 10 MW in 2030 correspond to those for 2020, with the exception of the average emission concentration for nitrogen oxides in natural gas combustion plants.

The 44th BImSchV (2019) requires compliance with a limit value of 150 mg/Nm³ for natural gas combustion plants from 2025 (with the addition of measurement uncertainty to the measured value). For this reason, 19 of the 65 measurement series on natural gas combustion plants whose nitrogen oxides measured values were above 139 mg/Nm³ if not taking the measurement uncertainty into account were set to the value 139 mg/Nm³. This takes into account the fact that own measurements have shown that a measurement uncertainty of around 11 mg/Nm³ must be added to a concentration of this magnitude. With the setting of 139 mg/Nm³, the limit value that comes into force in 2025 is complied with by the 19 plants. The changed values result in an average emission concentration weighted by annual operating hours of 110 mg/Nm³ (compared to 117 mg/Nm³ in 2020) for nitrogen oxides emissions from existing natural gas combustion plants in the 1 MW to under 5 MW range, and an emission concentration of 106 mg/Nm³ (compared to 126 mg/Nm³ in 2020) for existing plants in the 5 MW to less than 10 MW range.

Table 32 and Table 33 document the emission concentrations determined for existing fuel oil and natural gas combustion plants in 2030, i.e. for plants that were built before 20 December 2018. For more detailed reporting in accordance with Article 11 of the EU Directive (2015), the description is broken down into the capacity classes 1 MW to less than 5 MW and 5 MW to less than 10 MW.

Table 32: Mean emission concentration at 3 % O_2 for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for existing fuel oil plants with 1 - < 10 MW in 2030

Nominal heat output [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	22	164	< 0.961	0.00	< 0.646
5 - < 10	34	150	< 1.16	0.00	< 1.00

Note: If a value is labelled "<", the measured values were below the limit of quantification and were included in the average emission concentration with half the limit of quantification. No weighting was carried out according to annual operating hours, as the majority of the fuel oil plants had no or very few operating hours.
Source: CO data 2019 (UBA 2023a), other data own measurements (2020-2022)

Table 33: Mean emission concentration at 3 % O_2 for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for existing natural gas plants with 1 - < 10 MW in 2030

Nominal heat output [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	19	110	< 1.15	0.00	< 0.207
5 - < 10	21	106	< 1.93	0.00	< 0.100

Note: If a value is labelled "<", the measured values were below the limit of quantification and have been included in the average emission concentration with half the limit of quantification. All values except for CO are based on own measurement data and were weighted according to the annual operating hours of the measured plants. If NOx measured values were above 139 mg/Nm³, these were set to 139 mg/Nm³, as the plants must comply with the limit value of 150 mg/Nm³ applicable from 2025, adding a measurement uncertainty of approx. 11 mg/Nm³.
Source: CO data 2019 (UBA 2023a), other data from own measurements (2020-2022)

Table 34 and Table 35 document the resulting emission factors [mg/MJ] for existing fuel oil and natural gas plants in 2030, for which a conversion factor of 0.28 is applied to the average emission concentrations [mg/Nm³] (UBA 2023b).

Table 34: Emission factors for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for existing fuel oil plants with 1 - < 10 MW in 2030

Nominal heat output [MW]	CO [mg/MJ]	NOx [mg/MJ]	CH_4 [mg/MJ]	NMVOC [mgC/MJ]	Dust [mg/MJ]
1 - < 5	6.16	45.9	< 0.269	0	< 0.181
5 - < 10	9.52	42.0	< 0.325	0	< 0.280

Note: If a value is labelled "<", the measured values were below the limit of quantification and are included in the emission factor with half the limit of quantification. Conversion factor [mg/Nm³] to [mg/MJ]: 0.28.
Source: CO values based on 2019 (UBA 2023a), other data based on own measurements (2020-2022)

Table 35: Emission factors for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for existing natural gas plants with 1 - < 10 MW in 2030

Nominal heat output [MW]	CO [mg/MJ]	NOx [mg/MJ]	CH_4 [mg/ MJ]	NMVOC [mgC/ MJ]	Dust [mg/MJ]
1 - < 5	5.32	30.8	< 0.322	0	< 0.0580
5 - < 10	5.88	29.7	< 0.540	0	< 0.0280

Note: If a value is labelled "<", the measured values were below the limit of quantification and are included in the emission factor with half the limit of quantification. Conversion factor [mg/Nm³] to [mg/MJ]: 0.28.

Source: CO values based on 2019 (UBA 2023a), other data based on own measurements (2020-2022)

2.8 Emission factors of new fuel oil and natural gas plants with 1 MW to less than 10 MW nominal heat output in Germany

This chapter documents average emission concentrations for new fuel oil and natural gas combustion plants with a nominal heat output of 1 MW to less than 10 MW, i.e. for plants installed from 20 December 2018. With the exception of nitrogen oxides and carbon monoxide, the same values as used as for existing plants in chapter 2.6 are documented. For the other pollutants (TOC, NMVOC and dust), it is not assumed that the emission behaviour of new plants will change significantly. Emission factors per energy input are calculated from the average emission concentrations.

Average emission concentrations for new fuel oil plants are shown in Table 36. For nitrogen oxides emissions from new fuel oil plants, the value measured at a plant with 3.2 MW and commissioning year 2018 is used; for carbon monoxide emissions, the mean value is used that Germany reported to the EU as part of reporting in accordance with Article 11 (2) of the EU Directive (2015) and which results from measurements in 2019 on new plants. Table 37 shows the resulting emission factors.

Table 36: Mean emission concentration at 3 % O_2 for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for new fuel oil plants with 1 - < 10 MW

Nominal heat output [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	21	92.9	< 0.961	0	< 0.646
5 - < 10	21	92.9	< 1.16	0	< 1.00

Note: If a value is labelled "<", the measured values were below the limit of quantification and have been included in the average emission concentration with half the limit of quantification. All values except for CO are based on own measurement data. There was no weighting according to annual operating hours, as the majority of the fuel oil plants had no or very few operating hours. Only the emission concentration for NOx is based on measurements from a newer plant built in 2018. The values for CH_4, NMVOC and dust correspond to the emission concentrations for existing plants, as no relevant changes are assumed for these parameters in newer plants.

Source: CO data from 2019 (UBA 2023a), other data from own measurements (2020-2022)

Table 37: Emission factors for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for new fuel oil plants with 1 - < 10 MW

Nominal heat output [MW]	CO [mg/MJ]	NOx [mg/MJ]	CH_4 [mg/MJ]	NMVOC [mgC/MJ]	Dust [mg/MJ]
1 - < 5	5.88	26.0	< 0.269	0	< 0.181
5 - < 10	5.88	26.0	< 0.325	0	< 0.280

Note: If a value is labelled "<", the measured values were below the limit of quantification and are included in the emission factor with half the limit of quantification. Conversion factor [mg/Nm³] to [mg/MJ]: 0.28.
Source: CO values based on 2019 (UBA 2023a), other data based on own measurements (2020-2022)

For natural gas combustion plants (Table 38), the average nitrogen oxides values from own measurements on five new plants with 1 MW to less than 5 MW (built in 2019 or 2020) are used for new plants (scenario 1; for scenario 2, see chapter 2.9). For carbon monoxide emissions, the mean value is used that Germany reported to the EU as part of reporting in accordance with Article 11 (2) of the EU Directive (2015) and that results from measurements in 2019 at new plants. Table 39 shows the resulting emission factors.

Table 38: Mean emission concentration for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for new natural gas plants with 1 - < 10 MW, scenario 1

Nominal heat output [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mg C/Nm³]	Dust [mg/Nm³]
1 - < 5	19	78.9	< 1.15	0.00	< 0.207
5 - < 10	16	78.9	< 1.93	0.00	< 0.100

Note: If a value is labelled "<", the measured values were below the limit of quantification and have been included in the emission concentration with half the limit of quantification. All values except for CO are based on own measurement data and were weighted according to the annual operating hours of the measured plants; only the value for NOx is based on the measurement at five newer plants built in 2019 and 2020. The values for CH_4, NMVOC and dust correspond to the emission concentrations for existing plants, as no relevant changes are assumed for these parameters in newer plants.
Source: CO data from 2019 (UBA 2023a), other data own measurements (2020-2022)

Table 39: Emission factors for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for new natural gas plants with 1 - < 10 MW, scenario 1

Nominal heat output [MW]	CO [mg/MJ]	NOx [mg/MJ]	CH_4 [mg/MJ]	NMVOC [mgC/MJ]	Dust [mg/MJ]
1 - < 5	5.32	22.1	< 0.322	0	< 0.0580
5 - < 10	4.48	22.1	< 0.540	0	< 0.0280

Note: If a value is labelled "<", the measured values were below the limit of quantification and are included in the emission factor with half the limit of quantification. Conversion factor [mg/Nm³] to [mg/MJ]: 0.28.
Source: CO values based on 2019 (UBA 2023a), other data based on own measurements (2020-2022)

2.9 Emission factors of natural gas combustion plants with 1 MW to less than 10 MW nominal heat output in Germany in 2030 with a NOx limit value of 100 mg/Nm³

For nitrogen oxides emissions from natural gas plants with 1 MW to less than 10 MW, scenario 2 assumes that a limit value for nitrogen oxides in new and existing natural gas plants in Germany in 2030 must be complied with in line with the requirements in the Netherlands.

The NOx limit value in the Netherlands for natural gas combustion plants with 1 - <10 MW is 70 mg/Nm³ at 3 % O_2 (see Chap. 5.5.1), whereby the measurement uncertainty is deducted during the limit value check. According to the measurement data from the Netherlands (SCIOS 2022), this corresponds approximately to the definition of a NOx limit value of 100 mg/Nm³, if the measurement uncertainty is added to the measured value, as required in the 44th BImSchV for limit value verification in Germany.

Scenario 2 assumes that the majority of burners in existing natural gas plants in Germany will be replaced by low-NOx burners by 2030 in order to safely comply with the limit value.

The mean emission concentration for nitrogen oxides is the average value of the measurement at 1656 natural gas plants in the Netherlands (value without addition or deduction of measurement uncertainty). The measurements were taken in the period from January 2017 to July 2022 (SCIOS 2022). This results in an average emission concentration of 59.1 mg/Nm³ for nitrogen oxides in scenario 2 for new and existing plants.

The average emission concentration for carbon monoxide used in Scenario 2 is the same as in Scenario 1.

Table 40 documents the average emission concentrations. Table 41 shows the resulting emission factors.

Table 40: Mean emission concentrations for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for natural gas plants with 1 - < 10 MW with NOx limit value specification as in the Netherlands

Nominal heat output [MW]	CO [mg/Nm³]	NOx [mg/Nm³]	CH_4 [mg/Nm³]	NMVOC [mgC/Nm³]	Dust [mg/Nm³]
1 - < 5	19	59.1	< 1.15	0.00	< 0.207
5 - < 10	16	59.1	< 1.93	0.00	< 0.100

Note: If a value is labelled "<", the measured values were below the limit of quantification and have been included in the emission concentration with half the limit of quantification. The values from own measurements (CH_4, NMVOC, dust) were weighted according to the annual operating hours of the measured plants.

Source: CO data from 2019 (UBA 2023a), NOx data 2017-2022 (SCIOS 2022), other data own measurements 2020-2022

Table 41: Emission factors for carbon monoxide, nitrogen oxides, methane, NMVOC and total dust for natural gas plants with 1 - < 10 MW with NOx limit value specification as in the Netherlands

Nominal heat output [MW]	CO [mg/MJ]	NOx [mg/MJ]	CH_4 [mg/MJ]	NMVOC [mgC/MJ]	Dust [mg/MJ]
1 - < 5	5.32	16.5	< 0.322	0.00	< 0.0580
5 - < 10	5.38	16.5	< 0.540	0.00	< 0.0280

Note: If a value is labelled "<", the measured values were below the limit of quantification and are included in the emission factor with half the limit of quantification. Conversion factor [mg/Nm³] to [mg/MJ]: 0.28.

Source: CO data based on 2019 (UBA 2023a), NOx data based on 2017-2022 (SCIOS 2022), other data based on own measurements 2020-2022

2.10 Emissions from fuel oil and natural gas plants with a rated thermal input of 1 MW to less than 10 MW in Germany in 2020

In this chapter, emissions from fuel oil and natural gas combustion plants with a rated thermal input of 1 MW to less than 10 MW that do not require a licence are calculated for the year 2020. In the absence of more precise data, it is assumed that they correspond to the emissions from combustion plants with a nominal heat output of 1 MW to less than 10 MW (for an explanation, see Chap. 2.1). The calculations use the activity rates (energy consumption in 2020) and emission factors (based on own measurements except for CO) explained in the previous chapters.

The data from the ZIV (2019) shows that between 2015 and 2019, on average around 2 % of fuel oil and 3 % of natural gas plants were replaced each year in relation to the total stock.

It is therefore assumed for 2020 that the new plants installed in 2019 and 2020 will account for around 4 % of fuel oil plants and 6 % of natural gas plants. NOx and CO emission factors for new plants are used for this share of energy consumption.

Table 42 and Table 43 show the emission quantities that can be calculated using the activity rates (see chapter 2.4) and emission factors (see chapter 2.6 and 2.8) for the year 2020 from plants in Germany with 1 MW to less than 10 MW. For emissions of carbon monoxide and nitrogen oxides, specific emission factors for new plants built from 20 December 2018 onwards were taken into account on a pro rata basis.

Table 42: Emissions of carbon monoxide, nitrogen oxides, methane, NMVOC and total dust from fuel oil plants with 1 - < 10 MW in 2020

Rated thermal input [MW]	CO [t/a]	NOx [t/a]	CH_4 [t/a]	NMVOC [t/a]	Dust [t/a]
1 - < 5	6.88	50.5	< 0.301	0.00	< 0.203
5 - < 10	3.40	15.0	< 0.118	0.00	< 0.101
1 - < 10	**10.3**	**65.5**	**< 0.419**	**0.00**	**< 0.304**

Note: 96 % existing plants, 4 % new plants. If a value is labelled "<", the measured values were below the limit of quantification and have been included in the emission factor with half the limit of quantification.
Source: CO data from 2019 (UBA 2023a), other data from own measurements 2020-2022

Table 43: Emissions of carbon monoxide, nitrogen oxides, methane, NMVOC and total dust from natural gas plants with 1 - < 10 MW in 2020

Rated thermal input [MW]	CO [t/a]	NOx [t/a]	CH_4 [t/a]	NMVOC [t/a]	Dust [t/a]
1 - < 5	978	5 914	< 59.2	0.00	< 10.7
5 - < 10	468	2 786	< 43.6	0.00	< 2.26
1 - < 10	**1 446**	**8 700**	**< 103**	**0.00**	**< 12.9**

Note: 96 % existing plants, 4 % new plants. If a value is labelled "<", the measured values were below the limit of quantification and have been included in the emission factor with half the limit of quantification.
Source: CO data from 2019 (UBA 2023a), other data from own measurements 2020-2022

Table 44 shows the total emissions from fuel oil and natural gas plants with a rated thermal input of 1 MW to less than 10 MW in 2020.

Table 44: Sum of emissions of carbon monoxide, nitrogen oxides, methane, NMVOC and total dust from fuel oil and natural gas plants with 1 - < 10 MW in 2020

Energy source	CO [t/a]	NOx [t/a]	CH_4 [t/a]	NMVOC [t/a]	Dust [t/a]
Fuel oil	10.3	65.5	< 0.419	0.00	< 0.304
Natural gas	1 446	8 700	< 103	0.00	< 12.9
Total	**1 456**	**8 766**	**< 103**	**0.00**	**< 13.2**

Note: If a value is labelled "<", the measured values were below the limit of quantification and have been included in the emission factor with half the limit of quantification.

Source: CO data from 2019 (UBA 2023a), other data from own measurements 2020-2022

2.11 Emissions from fuel oil and natural gas plants with a rated thermal input of 1 MW to less than 10 MW in Germany in 2030

In this chapter, emissions from medium fuel oil and natural gas combustion plants with a rated thermal input of 1 MW to less than 10 MW are calculated for the year 2030. The calculations use the activity rates (energy consumption in 2030) and emission factors (own measurements except for CO) explained in the previous chapters.

For fuel oil plants, it is assumed - as explained above - that energy consumption in 2030 will be the same as in 2020. For natural gas plants, it is assumed that consumption will decrease by 11 % by 2030 (see Chapter 2.5).

Table 45 and Table 46 show the emission quantities for 2030 that can be calculated using the activity rates (see Chapter 2.5) in conjunction with the emission factors (see Chapter 2.7 and 2.8) from plants in Germany with 1 MW to less than 10 MW.

Two scenarios are calculated for nitrogen oxides emissions. Scenario 1 assumes that the limit value requirements of the 44th BImSchV (2019) for medium combustion plants with 1 MW to less than 10 MW must be complied with by 2030. For scenario 2, it is assumed that in 2030, natural gas combustion plants with 1 MW to less than 10 MW must comply with a limit value of 100 mg/Nm³ including the measurement uncertainty, corresponding to the situation in the Netherlands in 2020 (see chapter 5.5).

With regard to the renewal of existing plants, the data from the ZIV (2019) shows that in the 1 MW to less than 10 MW nominal heat output class, an average of around 2 % of fuel oil and around 3 % of natural gas plants were renewed annually between 2015 and 2019.

It is therefore assumed for 2030 that new plants built between 2019 and 2030 will account for 24 % of fuel oil plants and 36 % of natural gas plants. For this share of energy consumption, lower NO_x and CO emission factors are used to calculate emissions, based on measurements of plants built from 20 December 2018.

For NO_x from natural gas plants, scenario 1 is based on own measurements. In addition, NOx measurement values from existing plants that are above the limit value applicable from 2025 were set to 139 mg/Nm³ in order to comply with the limit value of 150 mg/Nm³ with an additional measurement uncertainty of around 11 mg/Nm³.

In scenario 2, it is assumed for NO_x emissions that the emission factor derived from the natural gas plant mix in 2020 from measurements in the Netherlands will be reached in Germany in 2030.

Table 45 shows the calculated emissions for fuel oil plants for the year 2030, Table 46 the calculated emissions from natural gas plants, there with scenario 1 and scenario 2 for NO_x.

Table 45: Emissions of carbon monoxide, nitrogen oxides, methane, NMVOC and total dust from fuel oil plants with 1 - < 10 MW in 2030

Rated thermal input [MW]	CO [t/a]	NOx [t/a]	CH_4 [t/a]	NMVOC [t/a]	Dust [t/a]
1 - < 5	6.82	46.0	< 0.301	0.000	< 0.203
5 - < 10	3.13	13.8	< 0.118	0.000	< 0.101
1 - < 10	**9.95**	**59.8**	**< 0.419**	**0.000**	**< 0.304**

Note: Energy consumption of existing plants 76 %, new plants 24 %. If a value is labelled "<", the measured values were below the limit of quantification and have been included in the emission factor with half the limit of quantification.
Source: CO data from 2019 (UBA 2023a), other data from own measurements 2020-2022

Table 46: Emissions of carbon monoxide, nitrogen oxides, methane, NMVOC and total dust from natural gas plants with 1 - < 10 MW in 2030

Rated thermal input [MW]	CO [t/a]	NOx scenario 1 [t/a]	NOx scenario 2 [t/a]	CH_4 [t/a]	NMVOC [t/a]	Dust [t/a]
1 - < 5	871	4 529	2 701	< 52.7	0.000	< 9.49
5 - < 10	386	1 938	1 186	< 38.8	0.00	< 2.01
1 - < 10	**1 257**	**6 467**	**3 887**	**< 91.5**	**0.00**	**< 11.5**

Note: Energy consumption shares scenario 1: existing plants 64 %, new plants 36 %. If a value is labelled "<", the measured values were below the limit of quantification and have been included in the emission factor with half the limit of quantification.
Source: CO data from 2019 (UBA 2023a), NOx data scenario 2 from 2017-2022 (SCIOS 2022), other data from own measurements 2020-2022

Table 47 summarises the emissions from fuel oil and natural gas plants with a rated thermal input of 1 MW to less than 10 MW, whereby NO_x emissions are calculated once without (scenario 1) and once with a NO_x limit value reduction to 100 mg/Nm³ (scenario 2). This results in emissions of around 1,300 tonnes of carbon monoxide, 6,500 tonnes of nitrogen oxides in scenario 1, around 3,900 tonnes of nitrogen oxides in scenario 2, less than 92 tonnes of methane, less than 12 tonnes of dust and no emissions of non-volatile organic compounds (NMVOC).

Table 47: Sum of emissions of carbon monoxide, nitrogen oxides, methane, NMVOC and total dust from fuel oil and natural gas plants with 1 - < 10 MW in 2030

Energy source	CO [t/a]	NOx scenario 1 [t/a]	NOx scenario 2 [t/a]	CH_4 [t/a]	NMVOC [t/a]	Dust [t/a]
Fuel oil	9.95	59.8	59.8	< 0.42	0.000	< 0.304
Natural gas	1 257	6 467	3 887	< 91.5	0.000	< 11.5
Total	**1 267**	**6 527**	**3 947**	**< 91.9**	**0.000**	**< 11.8**

Note: In scenario 1, NOx measured values that are above the limit value applicable from 2025 were set to 139 mg/Nm³ in order to comply with the limit value of 150 mg/Nm³ with the addition of around 11 mg/Nm³ measurement uncertainty. If a value is labelled "<", the measured values were below the limit of quantification and have been included in the emission factor with half the limit of quantification.

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Source: CO data from 2019 (UBA 2023a), NOx data scenario 2 from 2017-2022 (SCIOS 2022), other data from own measurements 2020-2022

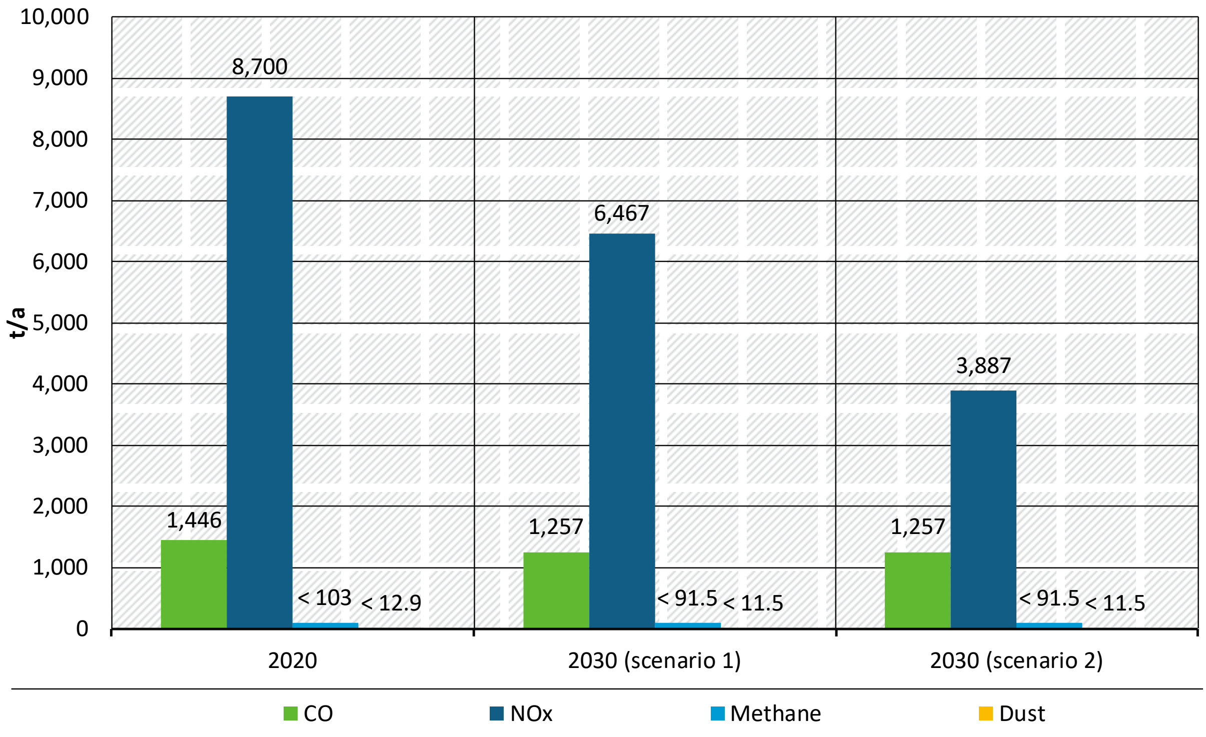
2.12 Development of emissions from natural gas plants with 1 MW to less than 10 MW in Germany between 2020 and 2030

Figure 11 shows the development of emissions from natural gas plants with 1 MW to less than 10 MW rated thermal input in Germany from 2020 to 2030.

For the year 2030, scenario 1 shows the development without a change in the NO_x limit value, scenario 2 shows the development with the specification of a NO_x limit value of 100 mg/Nm³ instead of 150 mg/Nm³ for natural gas combustion plants, which must be complied with by adding the measurement uncertainty.

Emissions of nitrogen oxides from natural gas combustion plants amounted to around 8,700 tonnes in 2020. Without legal changes, a reduction to around 6,500 tonnes is expected for 2030 (-25 %). If a limit value were set as in the Netherlands, nitrogen oxides emissions would fall to around 3,900 tonnes in 2030 (-55 %).

Figure 11: Development of emissions from natural gas combustion plants with a rated thermal input of 1 MW to less than 10 MW in Germany between 2020 and 2030



Note: Methane, dust with "<" as measurement results were partly below the limit of quantification (LOQ) and used for the emission factor with half the LOQ.

Source: own figure (Ökopol)

3 Emission measurements on medium fuel oil and natural gas plants with 1 MW to less than 10 MW in Germany

This chapter describes the procedure for 100 measurements on oil and gas combustion plants with a nominal heat output of 1 MW to less than 10 MW. Chapter 3.1 describes the procedure for selecting plants that are as representative as possible. Chapter 3.2 lists the emission reduction techniques used in the plants measured. Chapter 3.3 documents the parameters measured and the measurement methods used. Chapter 3.4 shows the measurement results as arithmetic mean values from three measurements, Chapter 3.5 presents the maxima of the measurement results plus measurement uncertainty in comparison to the limit values of the 44th BImSchV. In chapter 3.6 the measurement results of the individual parameters are checked for correlations.

3.1 Plants selection

The aim of the project was to carry out 100 measurements on oil and gas combustion plants with a nominal heat output of 1 to less than 10 MW, which are as representative as possible of the existing plants in Germany. For this purpose, measurements were carried out on plants that supply residential buildings with heat for heating and hot water, as well as plants in industrial companies that mainly generate process heat with the combustion plants.

To select the plants, contact was made with the authorities (Chapter 3.1.1) and with companies (Chapter 3.1.2) in the housing sector, heat contracting and industry.

The main obstacle to the participation of the plants in the measurements was the lack of a suitable measuring opening on the flue gas system with a size of three inches. This is not necessary for the measurements required to date. The vast majority of plants with a nominal heat output of 1 to less than 10 MW only have openings of ½ inch, which are suitable for measurements by the chimney sweepers, but were not sufficient for the measurement programme of the research project.

As the measurements were to be taken at the beginning of the coronavirus pandemic, the organisation was considerably more difficult, as those responsible were often difficult to reach when working from home and pandemic-related visiting restrictions for external specialist personnel led to a lack of readiness for measurements, especially in industrial companies.

3.1.1 Contacts with authorities

In July 2020, the project manager at the German Environment Agency informed the "Plant-related Air Quality Control / Major Accidents Prevention Committee" (AISV) in the "Federal/Länder Working Group on Air Quality Control" (LAI) about the project and asked for the names of contact persons who could support the project.

The following countries named persons who provided information on plants:

- Bavaria: Bavarian State Office for the Environment (BY-LfU)
- Hamburg: Hamburg Ministry for the Environment, Climate, Energy and Agriculture (HH-BUKEA)
- Hesse: Hessian Ministry for the Environment, Climate Protection, Agriculture and Consumer Protection (HE-UM)
- Lower Saxony: State Inspectorate Hildesheim (NI-GAA-HI)

- NRW: State Agency for Nature, Environment and Consumer Protection (NW-LANUV)
- Saxony: Saxon State Office for Environment, Agriculture and Geology (SN-LfULG)
- Saxony-Anhalt: State Administration Office (ST-LVWA)

The registers kept by 16 federal states for plants within the scope of the 44th BImSchV were still being set up during the period of plants selection in 2020/21 (plants have to be fully registered until the end of 2023). The persons responsible for the register at the authorities provided the project participants with initial lists of plants (MFA Plant Registry 2020), some of which were already available online. In addition, individual authorities also arranged contacts with plant operators.

3.1.2 Operator contacts

Ökopol contacted numerous companies in the housing industry, contracting companies and industrial companies to find suitable plants and to enquire about the agreement of the operators to carry out the measurements.

3.1.2.1 Housing industry

Contact was made with companies in the housing industry using the large companies researched on the internet. In September/October 2020, the following companies were contacted and asked about suitable plants and support for the project:

- Degewo
- Deutsche Wohnen
- Gewobag
- Howoge
- LEG Real Estate
- Nassauische Heimstätte
- SAGA GWG
- TAG Real Estate
- Vivawest
- Vonovia

Many of the companies in the housing industry stated that they use contracting companies to operate the heating plants in their residential buildings.

3.1.2.2 Contracting companies

The following heat contracting companies were contacted in September and October 2020 to ask them to take part in the project. Contacts were based on the major providers researched on the internet.

- Apleona HSG

- Caverion Germany
- Danpower
- Enercity Contracting
- Engie Germany
- Envia Therm
- ESB Heat
- Gasag Solution Plus
- G+E GETEC
- Hansewerk-Nature
- Sales & Solutions EnBW
- Savemaxx Contracting
- Spie Energy Solutions
- Techem Energy Contracting
- Urbana Energy Services

Thankfully, the company Danpower agreed to install new measuring nozzles with the required three-inch size in numerous plants with a nominal heat output of 1 MW to less than 10 MW, so that many measurements could be carried out in the plants operated by Danpower. Furthermore, the companies Enercity Contracting and Hansewerk-Natur provided plants for the measurements in residential buildings.

3.1.2.3 Industrial companies

Industrial companies were contacted on the basis of initial lists from the federal states on plants subject to the 44th BImSchV, information from authorities and on the basis of official monitoring plans for plants to be monitored in accordance with the Industrial Emissions Directive. (EU Directive 2010, IED Inspection Plans 2020)

Priority was given to contacting plant operators in the following sectors, in which plants with a nominal heat output of 1 to less than 10 MW were assumed:

- Automotive supplier,
- Breweries,
- Chemical industry,
- Printing industry,
- Manufacture of tools and machines,
- Wood-based panels industry,

- Plastics,
- Milk processing,
- Food processing,
- Abrasives production,
- Textiles,
- Animal feed production,
- Corrugated board production.

3.1.3 Plants selected for measurement

The 100 measurements were carried out on 79 plants between November 2020 and April 2022. 50 plants are used by contracting companies to heat residential buildings, 29 plants generate process heat for industrial plants. (Table 48)

Table 48: Number of plants measured and NACE code sector

Sector	Total	Industry	NACE code	Number of plants
Housing	50	District heating supply	40.30	50
Industry	29	Production of oils and fats	10.41	2
		Textile finishing	13.30	1
		Production of baked goods	10.71	9
		Wood-based panels industry	16.23	5
		Manufacture of other chemical articles	20.59	1
		Manufacture of other plastic goods	22.29	8
		Production of abrasives	25.73	1
		Automotive supplier (surface finishing/parts manufacturing)	25.61 / 29.32	2

21 plants are plants with multi-fuel burners, meaning that both gas and oil combustion could be measured in one plant. 51 plants have single-fuel burners for gas, seven plants have single-fuel burners for fuel oil. (Table 49)

Due to the difficulty of finding existing combustion plants with suitable measurement openings, in addition to 74 existing plants, five new gas-fired plants within the scope of the 44th BImSchV were also measured in consultation with the UBA, i.e. plants that were installed from 20 December 2018 and therefore have to comply with a stricter limit value for carbon monoxide and nitrogen oxides. (Table 49)

Table 49: Number of plants measured by type of burner, commissioning and sector

	Total	Existing plants (before 20 December 2018)	New plants (from 20/12/2018)	Housing	Industry
Single-fuel gas combustion plants	51	46	5	23	28
Multi-fuel combustion plants	21	21	0	21	0
Fuel oil single-fuel combustion plants	7	7	0	6	1
Total	**79**	**74**	**5**	**50**	**29**

Table 50 and Table 51 show the number and proportion of measured plants with oil or gas combustion, grouped by nominal heat output, compared with the total number of these plants in 2019 according to the survey by the Federal Association of Chimney Sweeps.

A comparison of the shares of measured plants per nominal heat output range with the total number of plants in Germany shows that plants with a low output (1 - < 2 MW) are slightly less represented in the measured plant mix for both oil-fired and gas-fired plants than in the total number of plants; plants with a higher output (4 - < 5 MW and 5 - < 10 MW) are proportionally slightly more represented in the measured plants. In the other output ranges, the shares of the measured plants roughly correspond to the shares in the total number of plants.

Table 50: Number and proportion of measured oil-fired plants compared with the total stock in Germany, grouped by nominal heat output

Nominal output Energy source	1 - < 2 MW	2 - < 3 MW	3 - < 4 MW	4 - < 5 MW	5 - < 10 MW	Total
Fuel oil combustion plants (measured plants)	12	5	1	5	5	28
Fuel oil combustion plants (entire plants)	1904	635	237	145	256	3177
Fuel oil operation (proportion measured)	43 %	18 %	3 %	18 %	18 %	100 %
Fuel oil operation (total share)	60 %	20 %	7 %	5 %	8 %	100 %

Source: Total number of plants: ZIV (2020)

Table 51: Number and proportion of measured gas-fired plants compared with the total stock in Germany, grouped by nominal heat output

Nominal heat output Energy source	1 - < 2 MW	2 - < 3 MW	3 - < 4 MW	4 - < 5 MW	5 - < 10 MW	Total
Natural gas combustion plants (measured plants)	25	18	7	12	10	72
Natural gas combustion plants (entire plants)	5310	1876	718	494	1018	9416
Natural gas combustion (proportion measured)	35 %	25 %	10 %	16 %	14 %	100 %
Natural gas combustion (total share)	56 %	20 %	8 %	5 %	11 %	100 %

Source of total plant portfolio: ZIV (2020)

The ZIV statistics are grouped according to the installed nominal heat output. In the 44th BImSchV (2019) and the MCPD, however, the plant is categorised according to the rated thermal input. Nominal heat output is the energy that the plant delivers to the heated system. If a plant only utilises the net calorific value of the fuel (not also the gross calorific value), the nominal heat output corresponds to the rated thermal input minus radiation losses of the boiler, the flue gas loss and the energy released with unburned fuel components. Radiation losses are 3-5 % for older boilers and less than 2 % for newer boilers (Haustechnik Dialog 2022). Heat losses in the flue gas are limited to a maximum of 9 % in accordance with the requirements of the 44th BImSchV.[5] This means that the ZIV data grouped according to nominal heat output is around 12-14 % below the installed rated thermal input in the worst case.

Among the plants measured, all of which operate without utilising condensing boilers, there was one plant with 9.765 MW at the upper limit of the nominal heat output group "5 - < 10 MW", which has a rated thermal input above 10 MW. This plant was included in the analysis due to the difficulties in finding plants in the 1-10 MW output range for the measurement. Before the 44th BImSchV came into force, the plant was also statistically included in the group up to < 10 MW, as the plants in the 1st BImSchV (2010) are grouped according to nominal heat output and not according to rated thermal input.

Appendix A anonymously lists the 79 plants measured by federal state, fuel, burner type, commissioning period and nominal heat output.

[5] For combustion plants that utilise the gross calorific value of the fuel by condensing the moisture in the flue gas rather than the net calorific value, the nominal heat output may be higher than the rated thermal input, as the rated thermal input always refers to the net calorific value.

3.2 Emission reduction techniques of the measured plants

3.2.1 Overview

Table 52 lists the emission reduction techniques reported by the operators for the measured plants in the questionnaire (see Annex B). The operators also mentioned techniques for increasing energy efficiency as emission reduction techniques, as the techniques lead to lower specific emissions in relation to the energy input.

It was asked whether emission reduction techniques were integrated during the installation or retrofitted. It was also asked whether low-sulphur fuel oil was used during the measurement in the plants with fuel oil or multi-fuel burners. (cf. Table 52)

Completed operator questionnaires are available for all 100 measurements at 79 plants. The completeness of the information depended on the knowledge of the responsible contact person. By supporting the manufacturers in analysing burner types using photos of type plates, it was possible to identify additional burners with NO_x reduction technique that were not specified by the operators (BDH 2022). It is possible that further operator information on emission reduction techniques is incomplete, as not all burner type plates were accessible for the creation of photos or were from manufacturers who did not participate in the type plate analysis.

In 100 measurements in 79 plants, the use of low NO_x burners to reduce nitrogen oxides was documented in 27 plants (34 %). Around a quarter of these low NO_x burners were retrofitted in existing plants. Six of the 27 plants were stated to have low NO_x burners and flue gas recirculation for nitrogen oxides reduction.

Of a total of 28 plants with fuel oil combustion that were measured, ten plants (36 %) stated that low-sulphur fuel oil was used. It should be noted that seven of the ten plants use multi-fuel burners that were predominantly operated with gas until 2021 and therefore tended to have older fuel oil stocks.

Lambda sensors or O_2 controls, which result in better burnout and therefore lower emissions of CO, methane, and TOC, were documented at nine of the 79 plants (11 %). Waste heat utilisation, which leads to specifically lower overall emissions, was reported by the operators at 19 of the 79 plants (24 %).

A combination of techniques was rarely mentioned. Two plants have low NO_x burners and O_2 control, three plants have O_2 control and utilise waste heat. One plant uses low-sulphur fuel oil and utilises waste heat.

Table 52: Operator and burner manufacturer information on emission reduction techniques at the measured plants

Emission reduction technique	Purpose of the technique	Fitted during instal-lation	Fitted as retrofit	Existing plants (before 20 December 2018)	New plants (from 20 December 2018)	Multi-fuel combustion plants
Low NO_x burner	Reduction of nitrogen oxides	21	6	24	3	4
Exhaust gas recirculation	Reduction of nitrogen oxides, improved burnout	1	5	6	0	1
Low sulphur fuel oil	Reduction of sulphur dioxides	-	-	10	0	7
Lambda sensor / O_2 control	Improving fuel utilisation and burnout, thereby reducing CO, methane and NMVOCs	7	2	9	0	1
Exhaust gas heat utilisation / heat exchanger	Improved fuel utilisation, resulting in lower specific emissions	n. s.	n. s.	19	4	2

Source: Operator questionnaire of 79 plants (own survey), manufacturer information on 21 burners (BDH 2022)

3.2.2 Techniques for reducing nitrogen oxides

In a total of 75 plants measured that were installed before 20 December 2019 ("existing plants"), low NO_x burners were used as nitrogen oxides reduction techniques in 24 plants (32 %); six of the plants also had flue gas recirculation. Low NO_x burners (without flue gas recirculation) were also documented at three of the five new plants measured (60 %). (see Table 52)

Low NO_x burners use a technique that optimises staged combustion in the flame zone. This produces a stable flame and reduces the formation of NO_x emissions.

With flue gas recirculation, the flue gas is fed back into the combustion chamber. This increases the burnout and therefore the energy efficiency, as the fuel is burnt out to a large extent. This minimises emissions of CO and organic compounds (TOC) and reduces NO_x emissions. The information on flue gas recirculation shows that the technique has mostly been retrofitted.

3.2.3 Techniques for the reduction of sulphur dioxides

At the time of the measurements in 2020-2022, only fuel oil with a sulphur content of up to 0.1 % may be marketed commercially (10th BImSchV 2019). Low-sulphur fuel oil accounted for 95 % of the total market in Germany in 2021 (BAFA 2022).

The use of low-sulphur fuel oil was reported in ten out of 28 of the oil-fired plants measured (36 %); seven of these ten plants have multi-fuel burners.

If the use of low-sulphur fuel oil was not explicitly stated by the operator, it is possible that the dual-fuel burner plants were primarily operated with natural gas for several years prior to the measurement. It is therefore possible that the measurements with oil combustion involved operation with older fuel oil stocks, which may have an increased sulphur content (>0.005 - 0.1 % S content). The introduction of low-sulphur fuel oil has also reduced the nitrogen content, as this corresponds to the sulphur content. A nitrogen content of less than 140 mg/kg is common in low-sulphur fuel oil; this maximum content, the quality of which forms a separate category in DIN 51603-1:2020, is generally not guaranteed by fuel suppliers (expert discussion 2022).

3.2.4 Techniques for improved burnout and increased energy efficiency

For 29 plants, techniques for better burnout or better energy utilisation were named: Waste heat utilisation and lambda sensor or O_2 control. These techniques increase the efficiency of combustion and thus also the efficiency of energy utilisation of the fuel.

In the case of flue gas heat utilisation, heat is used for purposes that require a relatively low temperature (e.g. to preheat combustion air or feed water). The use of the technique was predominantly reported by newer plants (one built in 2007, the others built between 2010 and 2020). Of the five new plants measured (year of construction 2020), four plants are operated with flue gas heat utilisation.

Lambda sensors (also known as O_2 control) enable an optimised air/fuel setting. This improves burnout and increases energy efficiency. This also reduces emissions of CO and organic compounds in particular and can also reduce NO_x emissions if the flame temperature remains stable. For most lambda sensors respectively O_2 control techniques, it is stated that they were already installed when the plant was installed. Three plants have both O_2 control and waste heat utilisation installed.

3.3 Measurements

3.3.1 Operator questionnaire and measurement protocol

A questionnaire was completed by the operator for each measured plant (see form in Appendix B). In addition, the measuring institute prepared a measurement report (see example in Appendix C).

The operator questionnaire contains contact details, information on the classification of the plant (purpose, fuel, commissioning, sector), on output, fuel, annual operating hours and typical mode of operation, as well as on maintenance and emission reduction techniques.

The measurement report contains information on the plant and the operating status (in particular the load) as well as measurement results, conversions of the measurement results to standard conditions and reference oxygen content as well as comments on special features of the measurement, in particular the nature of the measurement section and load fluctuations.

3.3.2 Measurement duration and measurement conditions

Where possible, three uninterrupted half-hour measurements were carried out on each plant. In cases where a plant was running at low or no load due to demand fluctuations, the measurement was interrupted to achieve a total of three 30-minute measurement periods where possible. In a few individual cases, the duration of the measurements had to be shortened, whereby a minimum measurement duration of 20 minutes was always guaranteed.

Measurements in the housing industry were carried out in the heating periods 2020/21 and 2021/22; measurements in industry from August to October 2021 and from February to April 2022.

3.3.3 Measured parameters, standards and technical rules used for measurement

Table 53 shows the measured parameters, the EN standards and VDI technical rules used.

In addition to the parameters carbon monoxide, nitrogen oxides, TOC, methane, dust and smoke number (only for oil combustion), the flue gas conditions were measured for each plant (volume flow, humidity, temperature, pressure, oxygen content) and the respective operating status of the plant, i.e. the mean load during the measurement period, was documented.

All measurements were carried out according to the standards with the date of publication listed in Table 53.

Table 53: Standards and technical rules used for measurements

Parameters	No.	Title	Published
CO	DIN EN 15058	Stationary source emissions - Determination of the mass concentration of carbon monoxide - Standard reference method: non-dispersive infrared	2017-05
TOC	DIN EN 12619	Stationary source emissions - Determination of the mass concentration of total gaseous organic carbon - Continuous flame ionisation detector	2013-04
Methane	DIN EN ISO 25140	Stationary source emissions - Automatic method for the determination of the methane concentration using flame ionisation detection (FID)	2010-12
NO_x	DIN EN 14792	Stationary source emissions - Determination of mass concentration of nitrogen oxides - Standard reference method: chemiluminescence	2017-05
Dust	DIN EN 13284-1	Stationary source emissions - Determination of low range mass concentration of dust - Part 1: Manual gravimetric method	2018-02
	VDI 2066 Sheet 1	Particulate matter measurement - Dust measurement in flowing gases - Gravimetric determination of dust load	2021-05
Smoke number	VDI 2066 Sheet 8	Measurement of particles - Dust measurement in flowing gases - Measurement of smoke number in furnaces designed for EL-type fuel oil	1995-09
O_2	DIN EN 14789	Stationary source emissions - Determination of volume concentration of oxygen - Standard reference method: Paramagnetism	2017-05
Volume flow	DIN EN ISO 16911-1	Stationary source emissions - Manual and automatic determination of velocity and volume flow rate in ducts - Part 1: Manual reference method	2013-06
Moisture	DIN EN 14790	Stationary source emissions - Determination of the water vapour in ducts - Standard reference method	2017-05
Measuring locations	DIN EN 15259	Air quality - Measurement of stationary source emissions - Requirements for measurement sections and sites and for the measurement objective, plan and report	2008-01
Determination of the measurement uncertainty	VDI 4219	Stationary source emissions - Determination of the measurement uncertainty of measured values obtained by emission measurements with manual or automated measurement methods	2009-08

3.3.4 Requirements for the flow conditions in the measuring plane

According to DIN EN 15259:2008-01, the following requirements for the flow in the measuring plane must be guaranteed for meaningful and reliable emission measurements:

1. the angle between the gas flow and the centre axis of the flue gas duct must be less than 15°;
2. there must be no localised negative flow;
3. There must be a minimum velocity depending on the measuring method used to determine the volume flow;
4. the ratio of the highest to the lowest local gas velocity in the measuring cross-section must be less than 3:1.

The above requirements are generally met in straight flue gas duct sections with an undisturbed inlet section of five hydraulic diameters upstream and an undisturbed outlet section of two hydraulic diameters downstream of the measuring cross-section and a distance to the end of the flue gas duct of at least five hydraulic diameters.[6] For an exhaust duct with a hydraulic diameter of 0.2 m, for example, this means that there should be an undisturbed inlet section of 1 m and an undisturbed outlet section of 0.4 m, and the end of the exhaust duct should be at least 1 m away.

However, falling below these dimensions for the length of the undisturbed inlet and outlet section does not mean that the measuring section is a priori unsuitable. Rather, the above criteria 1.) to 4.) are decisive as to whether representative measurements of the volume flow and the mass concentration of the air pollutants are possible in the measurement cross-section.

For all 100 measurements, points 1.) to 4.) were checked on site. The conditions were met. At flue gas systems where the recommended lengths of the undisturbed inlet and outlet sections could not be complied with, the total number of measuring points in the measuring cross-section was increased and the emission measurements were carried out as network measurements. This compensates for any otherwise increased measurement uncertainty.

3.3.5 Measurement uncertainty

DIN EN ISO 20988 (2007) was used to estimate the measurement uncertainty. This international standard provides comprehensive guidance and specific statistical methods for determining uncertainty from stationary sources, indoor air, workplace air and meteorology. VDI Guideline 4219 is a specification of DIN EN ISO 20988 and implements the general recommendations of the Guide to the Expression of Uncertainty in Measurement (GUM).

The measurement uncertainties were determined in accordance with DIN EN ISO 20988 (2007) in conjunction with VDI 4219 using the indirect approach:

"*In an indirect approach, scatter and systematic measurement deviations are determined in a first step separately for the input variables xi of the method model equation y = f(x1,..., xK), which is used to calculate a measurement result y. For this purpose, estimated values of the variances and covariances of the input variables xi can be provided by evaluating series of observations according to determination method A or by expert judgement according to determination method B. Subsequently, a weighted sum of the variances and covariances provides the uncertainty value sought.*" (DIN EN ISO 20988)

3.3.6 Measurement challenges

The following general conditions made it difficult to carry out the measurements:

[6] The hydraulic diameter is the ratio of four times the area of the measuring cross-section and the circumference of a measuring cross-section wetted by the fluid.

1. An undisturbed inlet and outlet section in accordance with DIN EN 15259 was only available in rare cases, so that the total number of measuring points had to be increased in most cases.
2. Plants were often not running at nominal load at the time of measurement. Various measurements were therefore carried out at low or strongly alternating loads.
3. In some cases, the plants were not running continuously at the time of measurement due to a lack of load. Plants switching on and off led to interrupted measurement periods, meaning that the measurements had to be carried out alternately.
4. The conditions on site were sometimes unsuitable for measurements. The limited working space and the difficult installation of the measuring devices made it hard to carry out the measurements.

3.4 Measurement results - mean value of three individual measurements

The measurement results for nitrogen oxides, dust, smoke number (fuel oil only), carbon monoxide, TOC, methane and NMVOC are documented below. An arithmetic mean was calculated from the three individual measurements, which generally lasted 30 minutes. All mean values of the measurements can be found in tabular form in the appendix D together with the associated average load condition during the measurements. Furthermore, Appendix E lists the maximum of the three measurements and the maximum plus the measurement uncertainty.

3.4.1 Nitrogen oxides

The measured nitrogen oxides values are mainly influenced by the temperature during combustion and by the nitrogen content of the fuel.

According to the burner manufacturers, the nitrogen content in fuel oil has fallen to usually less than 140 mg/kg as the sulphur content has been reduced. If older fuel oil stocks were used for a measurement, it is possible that no low-sulphur fuel oil was used and therefore a fuel with a higher nitrogen content was used. According to the burner manufacturers, natural gas exhibits significant fluctuations in nitrogen content. According to burner manufacturers, weather conditions also have an influence on measurement results: In humid ambient air in summer, lower nitrogen oxides values are to be expected, as the higher combustion air humidity causes more cooling of the flame than dry winter air. (Experts exchange 2022)

Table 54 shows the NO_x mean values from measurements taken during different seasons. The mean values were calculated from the 100 mean values of the three measurements per plant, usually lasting 30 minutes. The values are sorted according to mean values for fuel oil and natural gas combustion; the number of measured values is given for each mean value. Detailed measurement results, including the month of measurement, can be found in the appendix F (page 190).

No measurements were carried out on fuel oil plants in summer. The NO_x mean value of the fuel oil plants measured in spring/autumn is higher than that of the winter months, so that no cooling effect due to combustion air humidity could be observed.

For the seasonal NO_x mean values of the natural gas plants, there is also no trend towards lower emission values in summer with higher humidity. On the contrary, the mean value of the ten summer measurements is significantly higher than the mean value of the spring/autumn and winter seasons. Apparently, other influencing factors were decisive during the 72 NO_x measurements on natural gas plants.

Table 54: Comparison of NO_x mean values from measurements at different seasons of the year

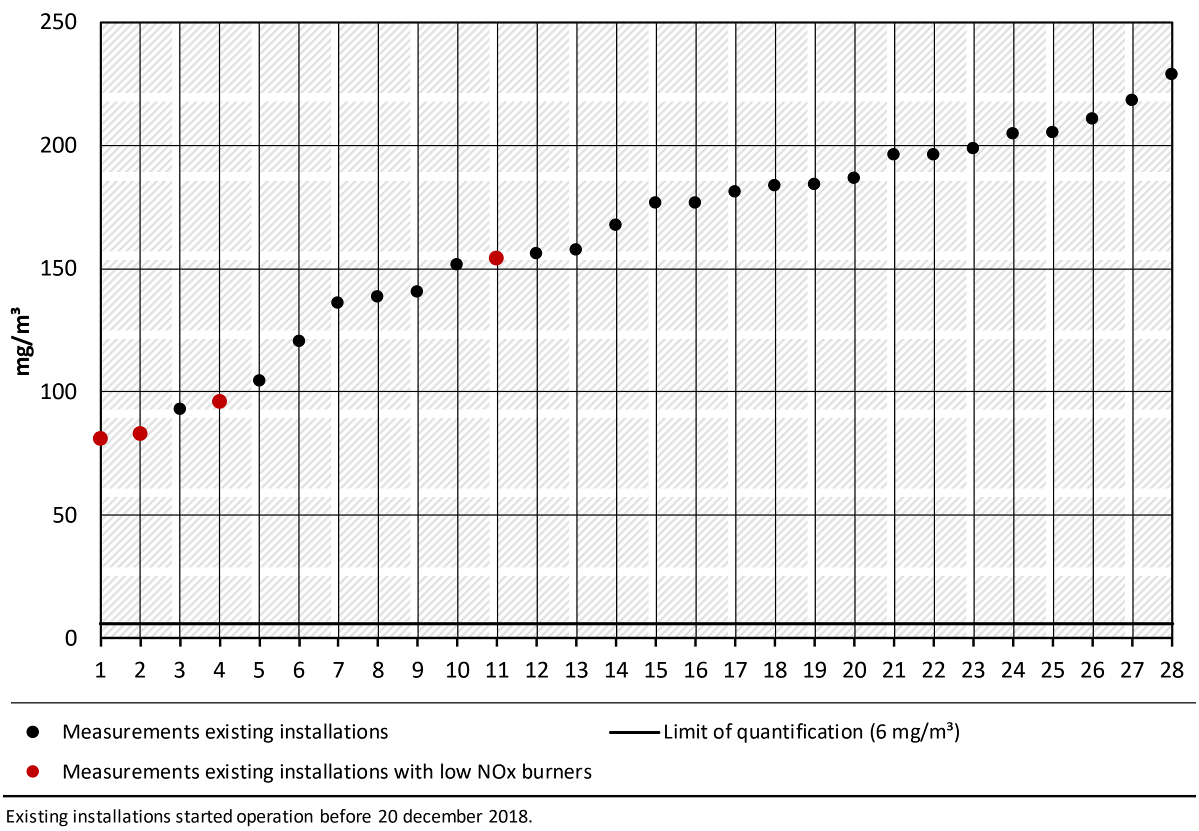
Season	Fuel oil NO_x as NO_2 [mg/m³]	Fuel oil Number of values	Natural gas NO_x as NO_2 [mg/m³]	Natural gas Number of values
Summer	-	-	141	10
Spring/Autumn	186	2	110	24
Winter	160	26	114	38

Note: Summer includes June/July/August; winter includes Dec/Jan/Feb
Source: own analysis

A systematic influence of the operating load on the measured NO_x level could not be determined during the measurement. Appendix H shows the three individual measured values of the 100 measurements and the respective mean load during each single measurement, in relation to the nominal power of the plant.

The 28 measurements of nitrogen oxides at fuel oil plants resulted in emission values between 81 and 229 mg/Nm³. No value was below the limit of quantification (6 mg/Nm³). (Figure 12)

Figure 12: Nitrogen oxides measured values - fuel oil plants (standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Source: own figure (Ökopol)

The measurements on fuel oil combustion plants were carried out in the period from November 2020 to February 2021 and from January to April 2022 and therefore in dry ambient air, which tends to lead to higher values. The nitrogen content of the fuel was not determined.

Three older plants (one installed in 1991 and two installed in 1994) use retrofitted low NO_x burners and thus achieve the lowest measured values (81/83/96 mg/Nm³). The respective load condition at the time of measurement was 67/80/100 %. With another low NO_x burner on a plant from 2013, 154 mg/Nm³ was measured at a load of 74 %.

The third-lowest measured value (93 mg/Nm³), which was measured at 80 % load, is a dual-fuel combustion plant installed in 2018. Low-sulphur fuel oil was used for the measurement, which tends to be low in nitrogen. A low NO_x burner is not installed here (BDH 2022). The plant also had low NO_x emissions (around 50 mg/Nm³) when measured in natural gas mode at 77 % load. The measurement was carried out at outside temperatures of around 0 °C, i.e. in dry winter air, which tends to lead to higher NO_x measured values due to the low combustion air humidity.

For the emission values 152/154/167/177/184/196/205/205/211 mg/Nm³, low-sulphur fuel oil was also used, which tends to be low in nitrogen.

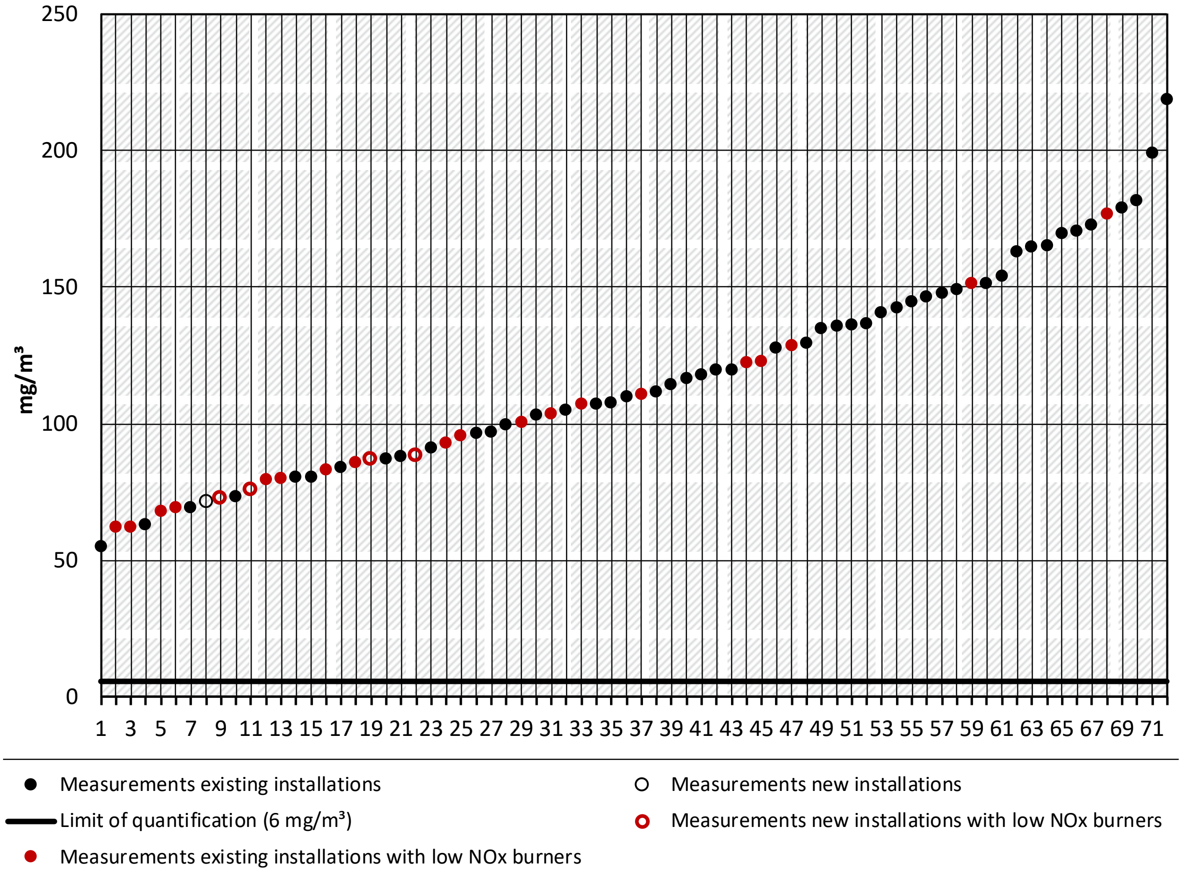
Burners with flue gas recirculation showed emission values of 139 and 156 mg/Nm³ in measurements with fuel oil combustion; a burner with lambda sensor emitted 120 mg/Nm³.

The plant with the highest NO_x value of 229 mg/Nm³ also has a relatively high CO value of 9.8 mg/Nm³. The plant was running at full load during the measurement. With four other very high NO_x values (218/211/205/205 mg/Nm³), the plants were running at 50 to 70 % load.

It is striking that five of the highest NO_x values in fuel oil operation (> 195 mg/Nm³) are dual-fuel burners and that these correspond to the highest NO_x values in natural gas operation in only two of the five cases (around 180 mg/Nm³), otherwise significantly lower values of 97/120/141 mg/Nm³ were measured at the same burner in natural gas operation.

The 72 measurements of nitrogen oxides at natural gas plants resulted in emission values between 56 and 220 mg/Nm³. No value was below the limit of quantification (6 mg/Nm³). (Figure 13 in which the five measurements on new plants are labelled with circular markings).

Figure 13: Nitrogen oxides measured values - natural gas plants (standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Existing installations started operation before 20 december 2018.

Source: own figure (Ökopol)

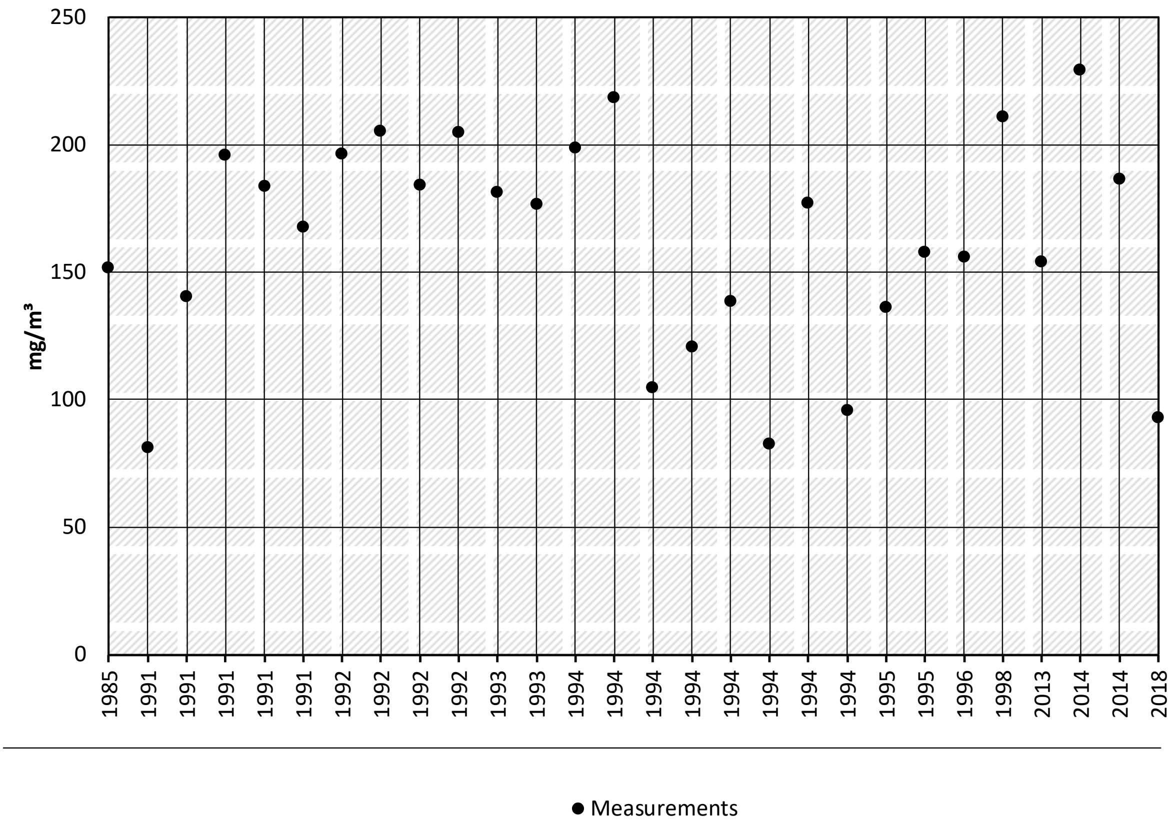
The natural gas combustion plants with low NO_x burners achieved the lowest NO_x values. The plant with the lowest NO_x measured value (56 mg/Nm³) is not a low NO_x burner (dual-fuel burner, installed in 2018). Two of the five new plants also achieved particularly low NO_x values (72/74 mg/Nm³). In eleven of the 28 plants with NO_x values below 100 mg/Nm³, the measurement was carried out at 75 to 100 % load, in a further 11 plants the load was between 39 and 50 % and the remaining six plants were operated at average loads between 16 and 33 % during the measurement.

For five plants, the operators stated that oxygen control was available, with which values of 80/86 mg/Nm³ were achieved twice in combination with low NO_x burners. In the other three plants with oxygen control, 85/123/129 mg/Nm³ NO_x were measured. For the remaining plants with low NO_x measurement values, no techniques were named by operators or manufacturers (based on type plate information) that contribute to NO_x reduction.

The two highest NO_x values for natural gas combustion (200/219 mg/Nm³) were measured at plants with single-fuel burners that went into operation in 2001 and 2012 and supply industrial plants with heating thermal oil. An exhaust gas recirculation system is installed in the plant with the highest NO_x value. The measurements of the highest values were carried out in August and September 2021, when lower NO_x values are to be expected with more humid ambient air. Load was 72 % at the highest value and 100 % at the second-highest value.

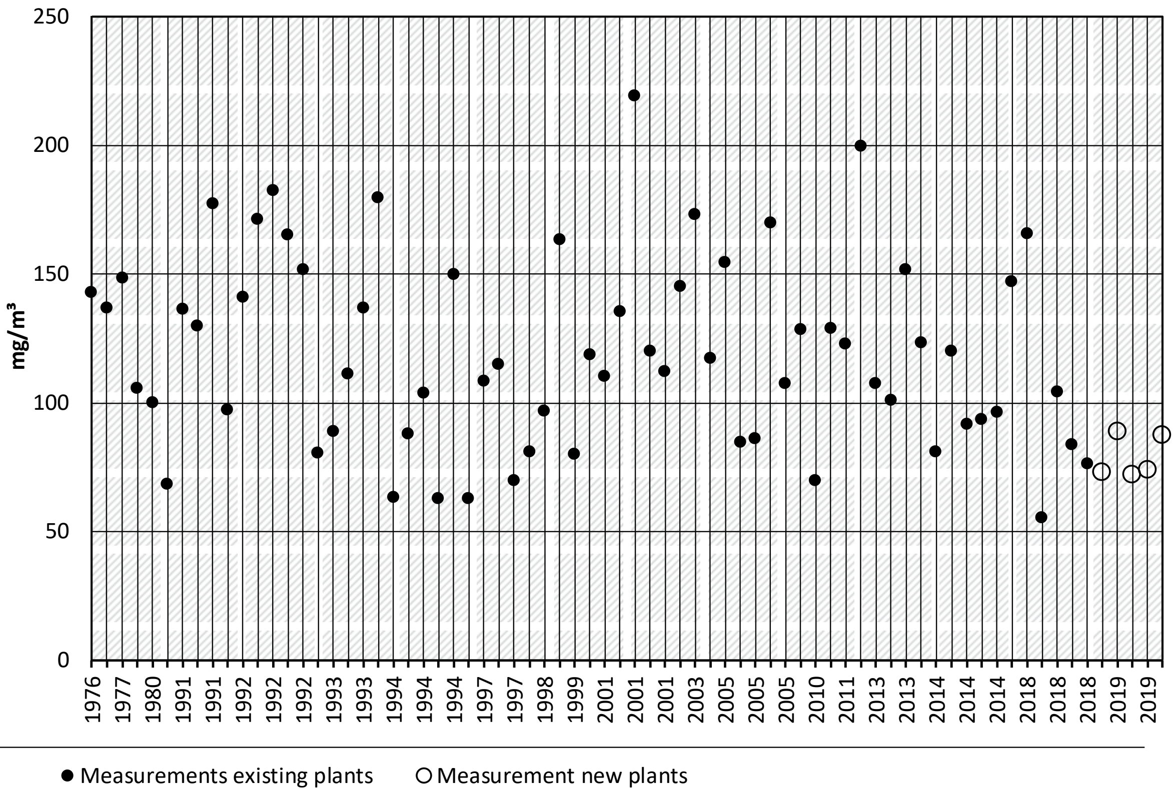
For correlations of the NO_x measured values with CO measured values, see chapter 3.6.8 (page 130). There is no correlation between the NO_x measured values and the age of the plant, neither for fuel oil combustion plants (Figure 14) nor for the existing natural gas combustion plants. The five new natural gas plants (installed from 20 December 2018) have low NO_x values. (Figure 15)

Figure 14: Nitrogen oxides measured values and year of installation - fuel oil plants (standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Source: own figure (Ökopol)

Figure 15: Nitrogen oxides measured values and year of installation - natural gas plants (standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

When determining emission factors for nitrogen oxides, two values from natural gas plants were not included in the calculation because unusually high CO, TOC and methane values were measured and the assessment was that, given the small number of measured values, it cannot be assumed that the values from these plants are representative of the overall spectrum of plants (see chapter 2).

3.4.2 Dust

In principle, due to the low mineral content of light fuel oil and the lack of soot formation in natural gas, very low dust concentrations can be expected in the flue gas that are close to the limit of quantification. It is possible that deposits are introduced into the dust measurement when a boiler is "cycled" (switched on/off). These can originate from boiler corrosion and from contamination during mixed operation with fuel oil and influence the measurement of emissions in natural gas operation. In addition, the combustion air of the boiler can be contaminated with dust due to impurities in the outside air, which can also be detected by the measurement.

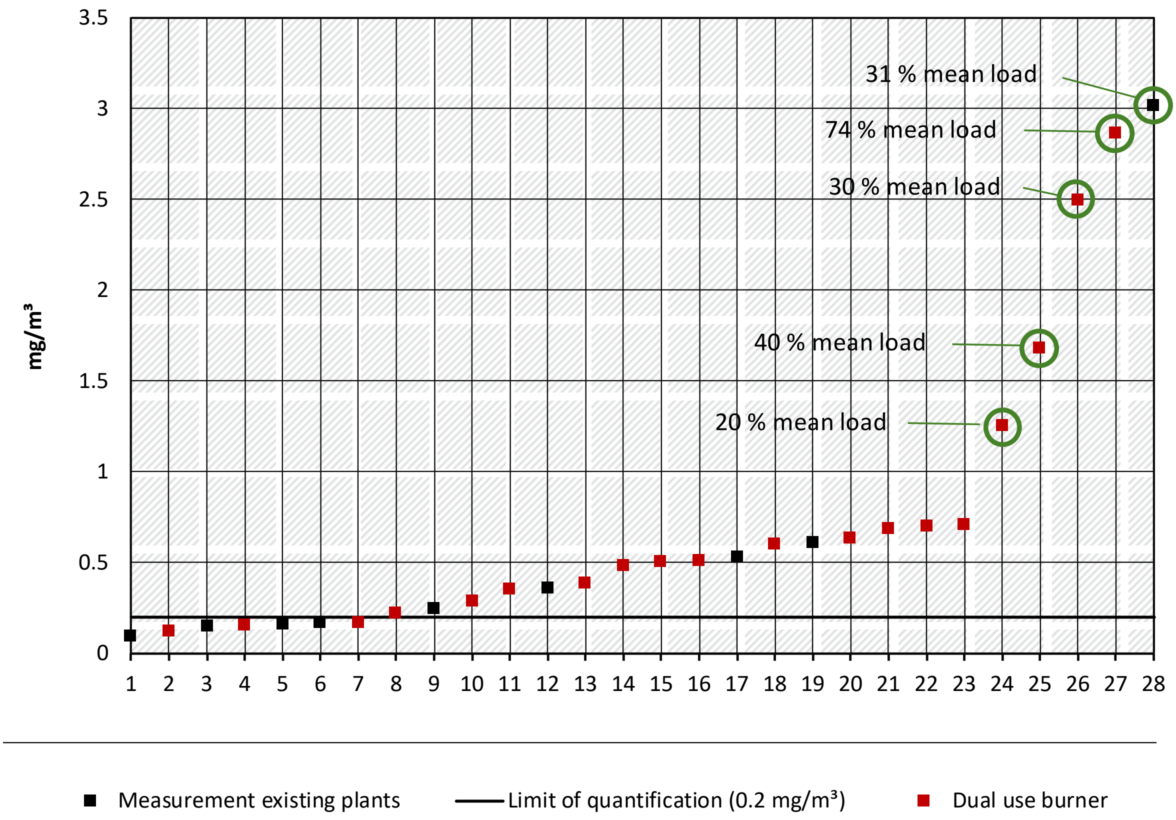
The 28 measurements of dust at fuel oil plants resulted in emission values between 0.095 and 3.0 mg/Nm³. Seven values were below the limit of quantification (0.2 mg/Nm³). (Figure 16)

Five of the 28 measured values for dust in fuel oil boilers (18 %) are elevated in the range of 1.3 to 3 mg/Nm³, nine other measured values (32 %) are slightly elevated in the range of 0.5 to 1 mg/Nm³. As a rule, the highest dust values are from plants installed between 1991 and 1996; one exception is a boiler from 2013.

The increased dust values are - with three exceptions - also associated with increased CO values, which were above the CO median (4.3 mg/Nm³). Two of the three highest CO values (27/32 mg/Nm³) are also associated with the highest dust values of 1.3/2.5 mg/Nm³. It is striking that another high CO value (9.8 mg/Nm³) is associated with a very low dust value below the limit of quantification (< 0.2 mg/Nm³). Very high smoke numbers (1.5/0.9) are only associated with two of the five highest dust values (1.3/2.5 mg/Nm³). Another high smoke number (0.8) is linked with a dust emission of 0.5 mg/Nm³; the associated CO value is comparatively high at 5.8 mg/Nm³.

During the measurements, four of the five highest dust average values of fuel oil combustion were operated with a particularly low load (20/30/31/40 %), which can be a reason of unfavourable combustion conditions, especially when starting the combustion.

Figure 16: Dust measured values - fuel oil plants (standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Source: own figure (Ökopol)

The 72 measurements of dust at natural gas plants resulted in emission values between 0.088 and 2.5 mg/Nm³. 36 values were below the limit of quantification (0.2 mg/Nm³). (Figure 17)

Seven of the 72 measured values for dust in natural gas combustion plants (10 %) are elevated in the range of 1 to 2.5 mg/Nm³, five others (7 %) are slightly elevated in the range of 0.5 to 1 mg/Nm³. The plants with elevated dust values have slightly different installation years, ranging from 1976 to 2013.

The value of 1.6 mg/Nm³ is associated with a particularly high value in the CO measurement of 1,240 mg/Nm³ as well as particularly high values for TOC (93 mg/Nm³) and methane (98 mg/Nm³), which indicates a suboptimal burner setting. The other elevated dust values show slightly increased CO values in the range of 1.7 to 5.4 mg/Nm³. With three exceptions

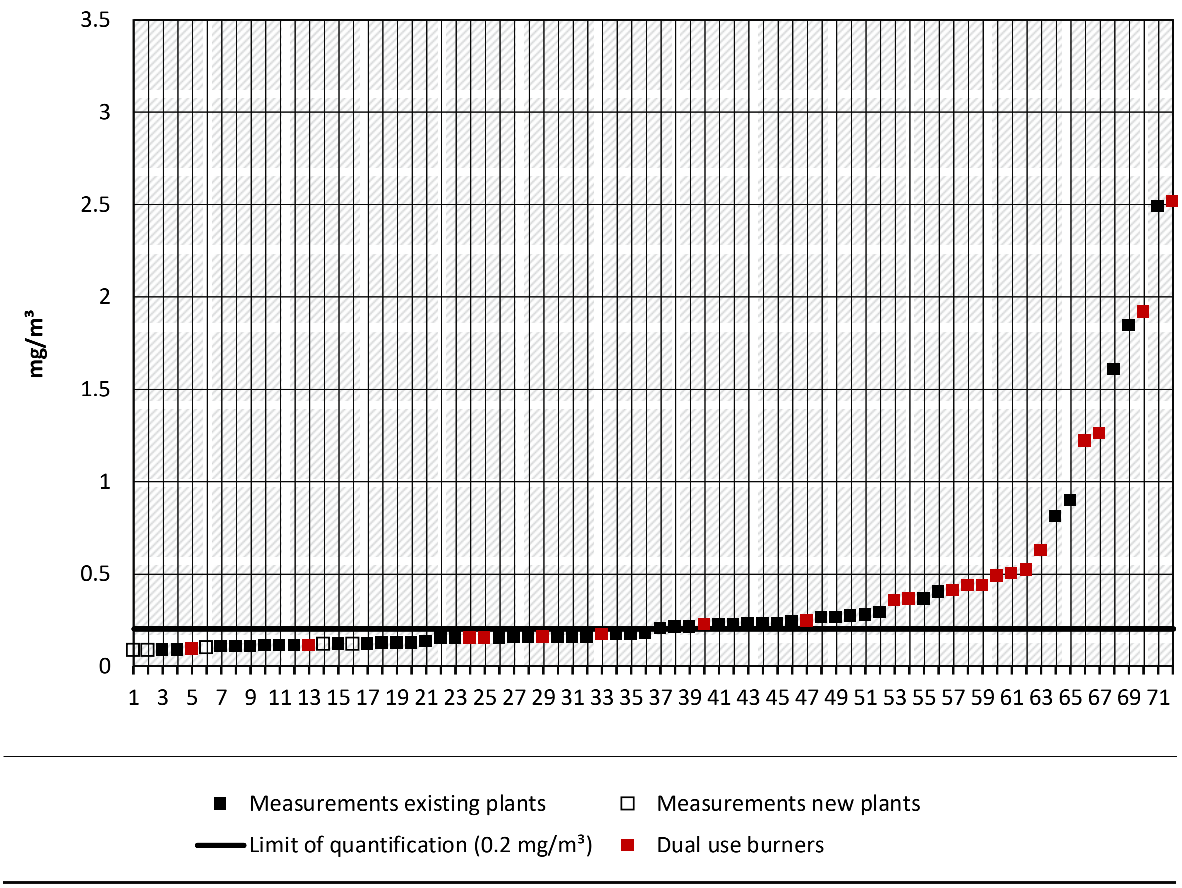
(1.7/2.1/2.6 mg/Nm³), the CO values with increased dust values are above the CO median (2.7 mg/Nm³), which indicates particularly unfavourable combustion conditions. It is striking that two further elevated CO values (11/13 mg/Nm³) and one particularly high CO value (2,761 mg/Nm³) are associated with very low dust values below 0.5 mg/Nm³.

A particularly low load (20/28/40 %) can only be observed in the measurements with increased dust values for natural gas combustion in three cases with slightly increased dust values (around 0.5 mg/Nm³). The load was otherwise 50 % or higher (50/52/52/60/65/74/87/95/100 %).

At the highest mean dust value (2.52 mg/Nm³), the inlet section with 0.8 times the diameter instead of 5 times the diameter of the flue gas pipe was not optimal. In addition, the burner stopped because of insufficient heat demand. For the two highest dust values of the three individual measurements (4.5/1.9 mg/Nm³), the plant was running at 60 % load, for the third highest measurement value (1.2 mg/Nm³) at 30 % load.

At the second highest dust mean value (2.49 mg/Nm³), the plant was running at full load. Two of the three individual measurements were at 0.79 mg/Nm³ and in the other case below the limit of quantification (0.2 mg/Nm³). During the third individual measurement, the boiler plant supplied more heat than was consumed on the demand side, resulting in shutdowns and interruptions to the measurement; the measured value was 5.7 mg/Nm³. The conditions for an undisturbed inlet and outlet section were not met (2.3 instead of 5-fold and 1.2 instead of 2.0-fold diameter).

Figure 17: Dust measured values - natural gas plants (standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

During the third highest dust average value (1.9 mg/Nm^3), the plant was running at 60 % load; the measured values of the three measurements gave approximately the same results. The conditions for an undisturbed inlet section were not met with 0.8 instead of 5 times the exhaust pipe diameter.

At the fourth highest dust average value (1.9 mg/Nm^3), the plant was running at around 95 % load, which was, however, adjusted (temperature-controlled) to the fluctuating demand. The measuring conditions were unfavourable (rectangular duct with control flaps directly at the measurement opening).

The correlation of the dust values with the smoke number and with carbon monoxide is assessed in chapters 3.6.6 (page 126) and 3.6.7 (page 127).

When determining emission factors for dust in natural gas plants, all values above 1 mg/Nm^3 were excluded from the emission factor calculation because external influences on the measurement are assumed (boiler cycling and therefore possible dust input from deposits). In addition, all measurements for natural gas operation on mixed boilers were excluded from the calculation of the emission factor calculation to ensure that the emission factor does not include any measured values that were influenced by deposits from fuel oil operation (for excluded values, see data marked in bold in Table 82). As a result, 51 measured values from natural gas plants were used to calculate the emission factor (see chapter 2), 25 of which were below the limit of quantification of 0.2 mg/Nm^3 and were included with half the limit of quantification.

Of the 28 measurements from fuel oil plants, all measured values were included in the emission factor; of these, seven measured values were below the limit of quantification of 0.2 mg/Nm^3; they were included in the emission factor with half the limit of quantification.

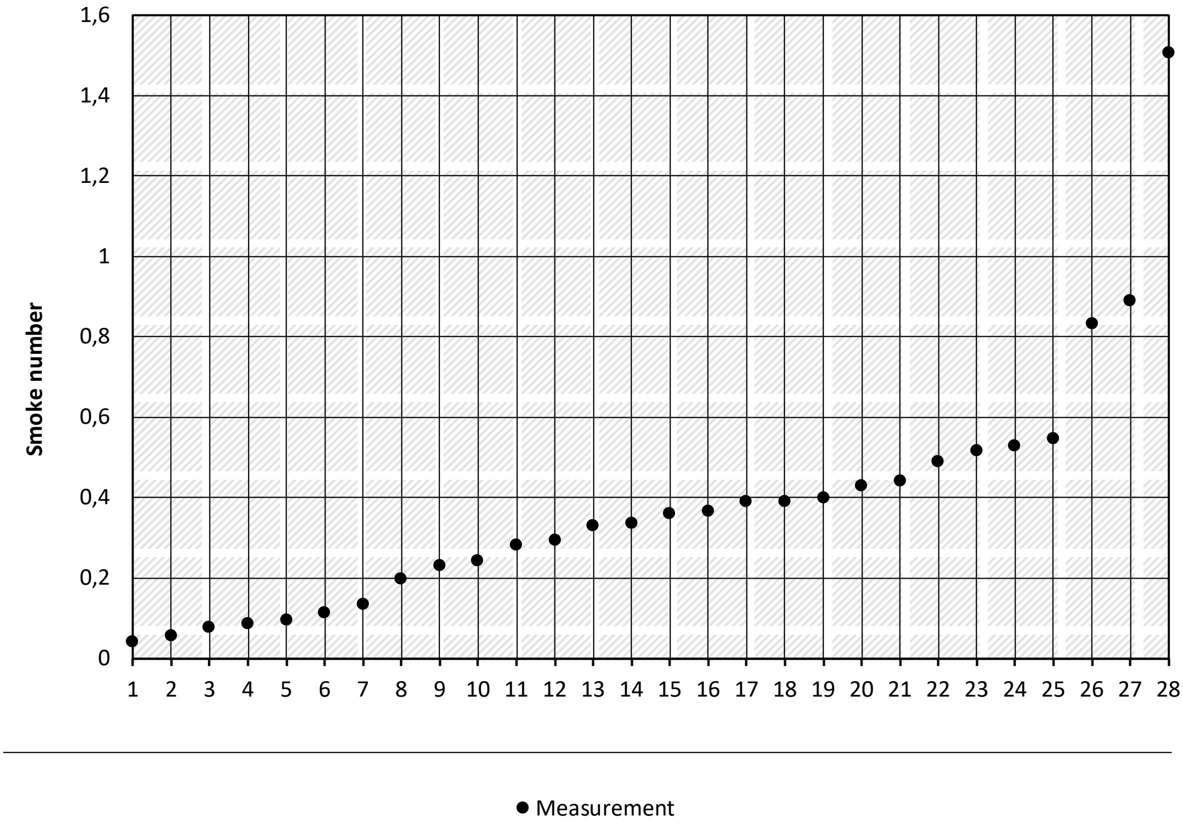
3.4.3 Smoke number

An increased smoke number indicates soot formation associated with incomplete combustion.

The 28 measurements on fuel oil plants resulted in smoke number values of 0.04 to 1.5 (Figure 18). The two highest values (0.9/1.5) were also associated with high values in the CO measurement (32/27 mg/Nm^3) and the second highest value was also associated with a high methane value (1.8 mg/Nm^3), which indicates a sub-optimal burner setting. The third-highest smoke number value (0.8) is also associated with an increased methane value (1.2 mg/Nm^3), as well as a CO value of 5.8 mg/Nm^3, which is above the CO median (4.3 mg/Nm^3). Conversely, it is striking that another relatively high CO value (9.8 mg/Nm^3) is associated with a very low smoke number (0.087). Increased TOC values (1.7/1.8/2.7 mg/Nm^3) do not correspond with an increased smoke number.

The correlation of the smoke number with dust values is analysed in chapter 3.6.6 (page 126).

Figure 18: Smoke number measured values - fuel oil plants (standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Source: own figure (Ökopol)

3.4.4 Carbon monoxide

Increased CO values indicate unfavourable combustion conditions, which are mainly caused by a suboptimal combustion air supply. Load fluctuations with burner cycling can also lead to increased CO values due to sub-optimal conditions when igniting the flame.

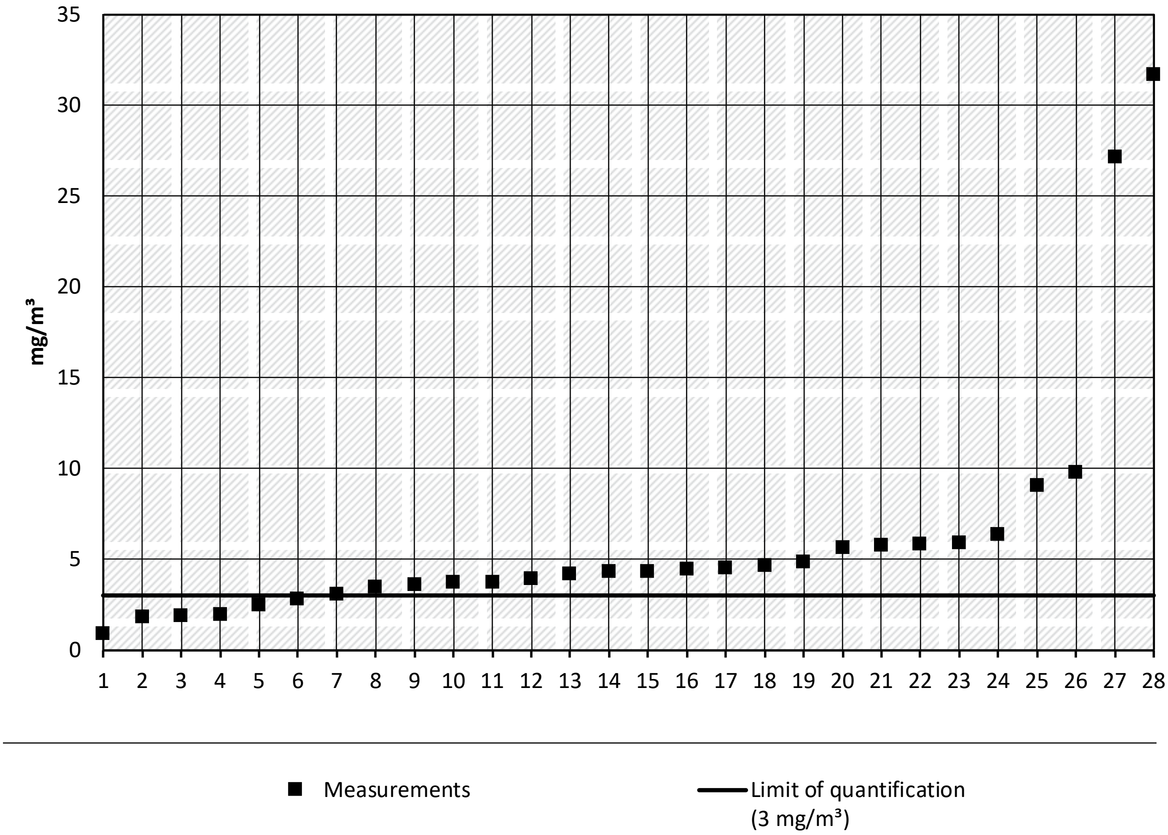
The 28 measurements of carbon monoxide at fuel oil plants resulted in emission values between 0.90 and 32 mg/Nm^3. Apart from two particularly high values, all values were below 10 mg/Nm^3. Six values (21 %) were below the limit of quantification (3 mg/Nm^3). (Figure 19)

The two highest CO values (27/32 mg/Nm^3) were measured on plants built in 1991 and 1993, with heavy cycling of the boilers and an average load of only 20 and 30 % respectively. In both cases, a particularly high smoke number was measured; in one case, relatively high emissions of methane (1.8 mg/Nm^3) and TOC (1.4 mg/Nm^3) were measured simultaneously.

The third-highest CO value (9.8 mg/Nm^3) was measured on a plant built in 2014 operated at full load and associated with a particularly high NO_x value of 229 mg/Nm^3, which indicates a suboptimal burner setting. The fourth-highest CO value (9.2 mg/Nm^3) from a plant built in 1991 also indicates a suboptimal burner setting, as at 40 % load a high NO_x value (184 mg/Nm^3) and a high methane value (1.9 mg/Nm^3) were measured.

For correlations of carbon monoxide with other parameters, see chapter on TOC 3.6.3 (page 119), for methane chapter 3.6.4 (page 122), on the smoke number chapter 3.6.4 (page 122) and on dust chapter 3.6.7 (page 127).

Figure 19: Carbon monoxide measured values - fuel oil plants (standardised, 3 % reference oxygen content, average value from three measurements, usually 30 minutes each)



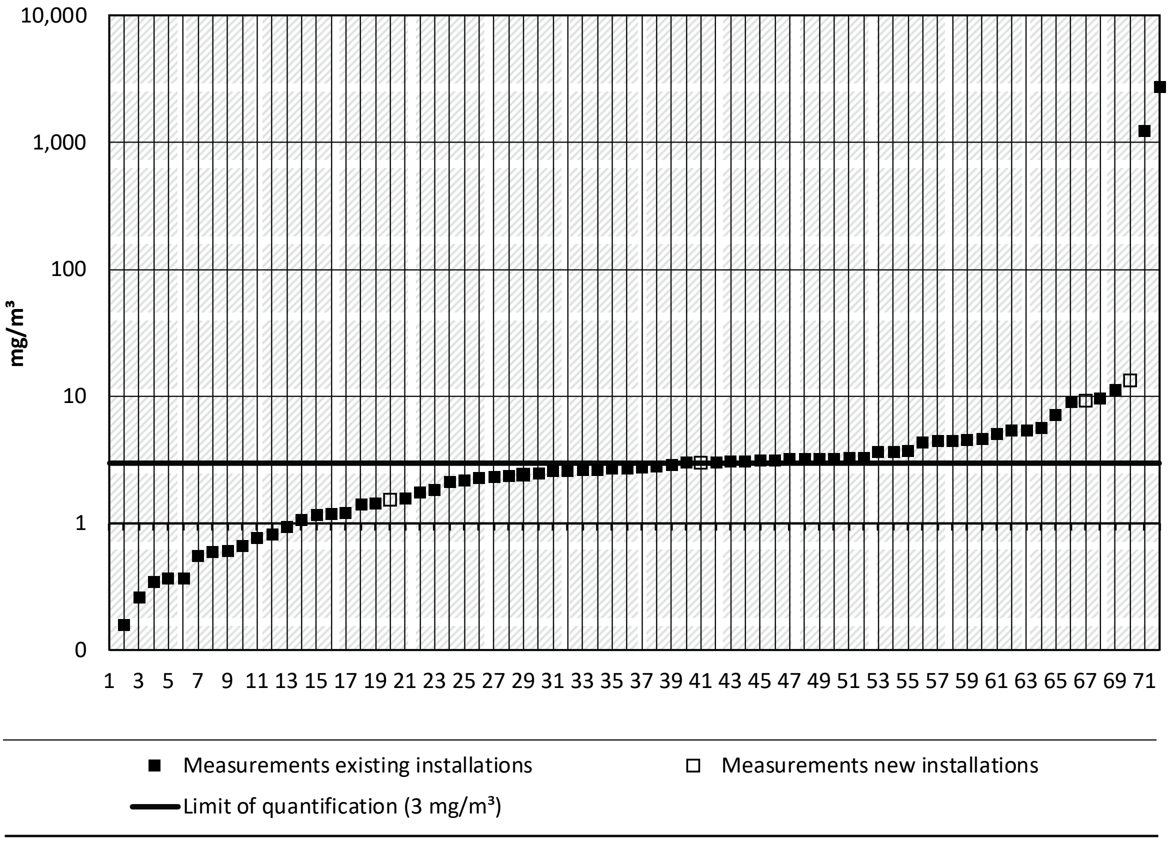
Source: own figure (Ökopol)

The 72 measurements of carbon monoxide at natural gas plants resulted in emission values between 0 and 2761 mg/Nm³. With 42 values, more than half of the measured values (58 %) were below the limit of quantification (3 mg/Nm³). Apart from two particularly high values (1240/2761 mg/Nm³) and two other elevated values, measured values were below 10 mg/Nm³. (Figure 20 showing all values, Figure 21 excluding the two highest values).

The two other elevated CO measurement values (11/13 mg/Nm³) originate from plants that were installed in 2015 and 2020. The mean load during the measurement was around 50 %. The values were also associated with increased emission values for TOC (3.3/1.6 mg/Nm³) and methane (3.6/1.1 mg/Nm³), which indicates a non-optimal burner setting.

The two highest values (1,240/2,762 mg/Nm³) were measured on boilers installed in 2001. They were operated at a mean load of 65 % and 29 % respectively during the measurement. The measured values indicate a sub-optimal burner setting, as particularly high values for TOC (93/594 mg/Nm³) and methane (98/603 mg/Nm³) were measured at the same time, as well as a particularly high value for dust (1.6 mg/Nm³) in one case.

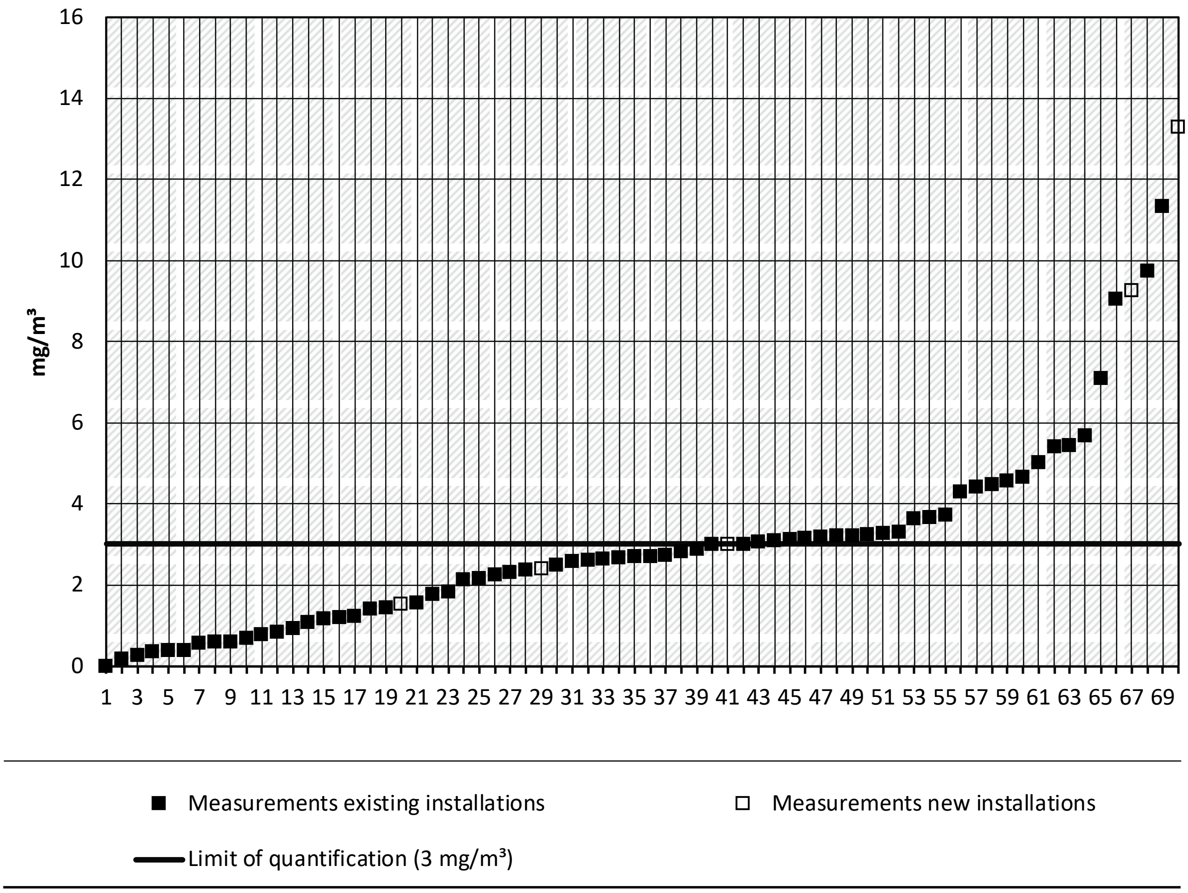
Figure 20: Carbon monoxide measured values - natural gas plants (logarithmic; standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Existing installations started operation before 20 december 2018.

Source: own figure (Ökopol)

Figure 21: Carbon monoxide measured values - natural gas plants (without two highest values; standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Existing installations started operation before 20 december 2018.

Source: own figure (Ökopol)

For the calculation of the emission factor for carbon monoxide, the set of measured data was significantly smaller than the data already available at the German Environment Agency (UBA 2023a), which Germany used for emissions reporting to the EU in accordance with Article 11 (2) MCPD. The data originate from measurements carried out by the Bavarian State Association of Chimney Sweeps on 3475 natural gas and 1524 fuel oil combustion plants, as well as data from the federal states from measurements on 490 combustion plants requiring a permit (321 natural gas and 169 fuel oil combustion plants). The particularly high emission values measured in the project have a considerable influence on the mean value of the measurements, whereby it is unclear whether such high individual values are also representative for a larger data collective. For this reason, the set of measured data was not used for the emissions factor calculation (see chapter 2).

3.4.5 Total organic carbon (TOC)

Increased emission values of total organic carbon (TOC) indicate incomplete combustion, which is primarily caused by a sub-optimal combustion air supply, same as with high carbon monoxide emissions. Load fluctuations with burner cycling can also lead to increased TOC values due to sub-optimal conditions when igniting the flame.

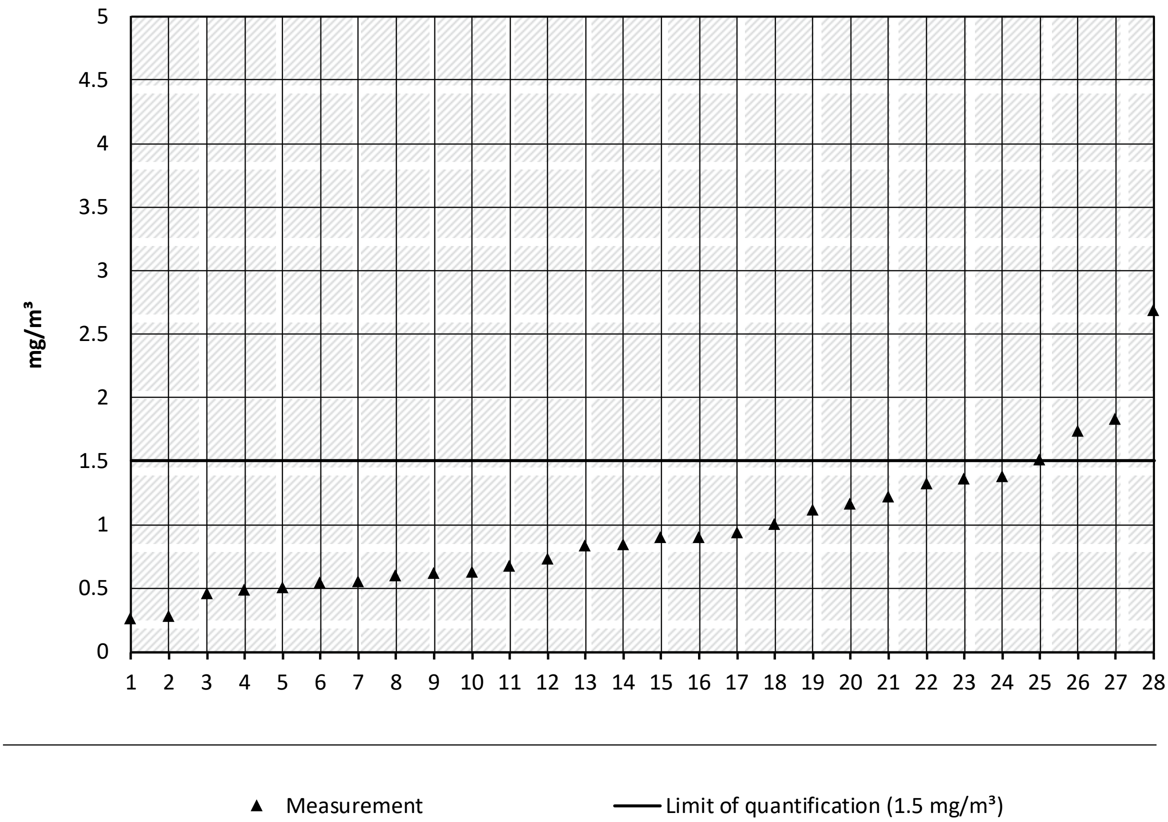
The 28 TOC measurements at fuel oil plants resulted in emission values between 0.26 and 2.7 mg/Nm³. With 24 values, the majority (86 %) were below the limit of quantification (1.5 mg/Nm³); four values were between 1.5 and 3 mg/Nm³. (Figure 22)

The four highest TOC values of the fuel oil combustion plants are not associated with increased carbon monoxide or smoke number values. The load was 47/50/38 % and only 10 % for the highest TOC value, which can also cause sub-optimal combustion.

The 72 measurements of TOC at natural gas plants resulted in emission values between 0.25 and 594 mg/Nm³. The majority of the 50 TOC values (69 %) were below the limit of quantification (1.5 mg/Nm³). Apart from two particularly high TOC values (93/594 mg/Nm³), all other values were below 5 mg/Nm³ (Figure 23, Figure 24 excluding the two highest values).

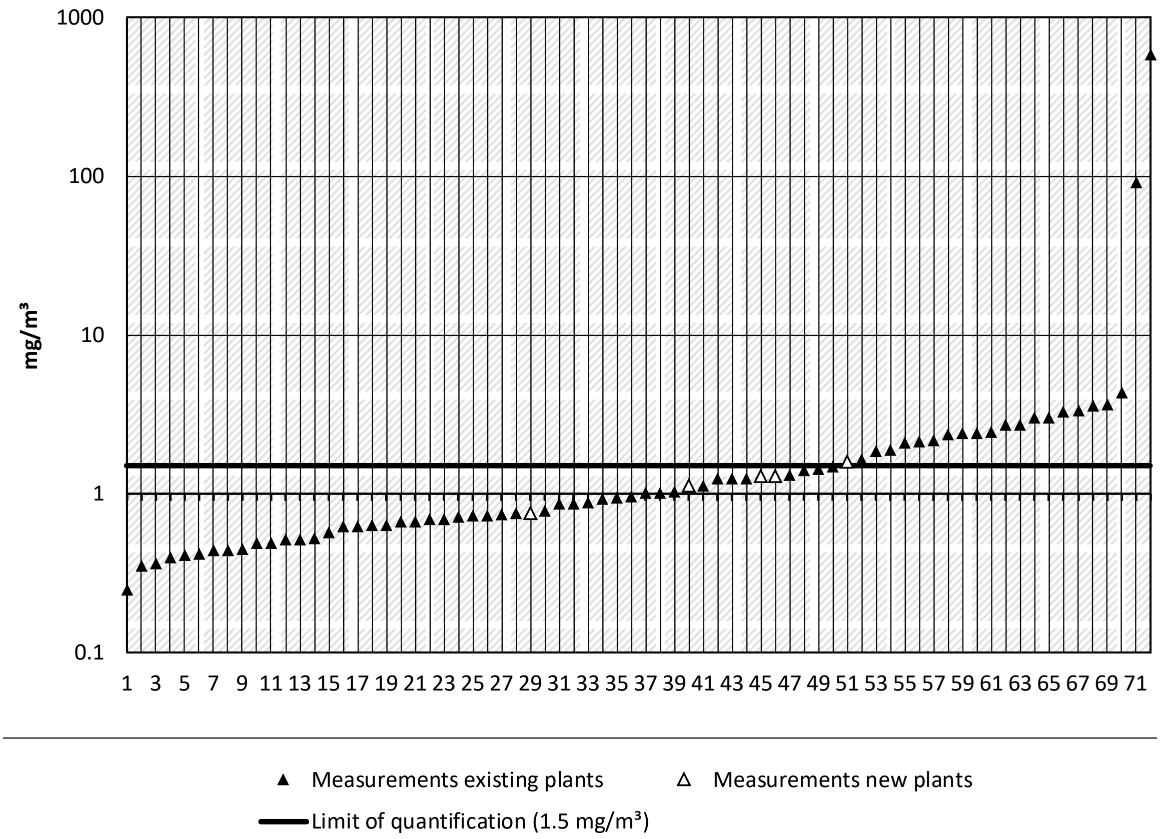
The two highest TOC values are from plants installed in 2001. The particularly high TOC values are accompanied by particularly high values for CO and methane and indicate a sub-optimal burner setting; in one case, the low load (29 %) contributes to the unfavourable conditions, in the other case the measurement was taken at a load of 65 %.

Figure 22: TOC measured values - fuel oil plants (standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Source: own figure (Ökopol)

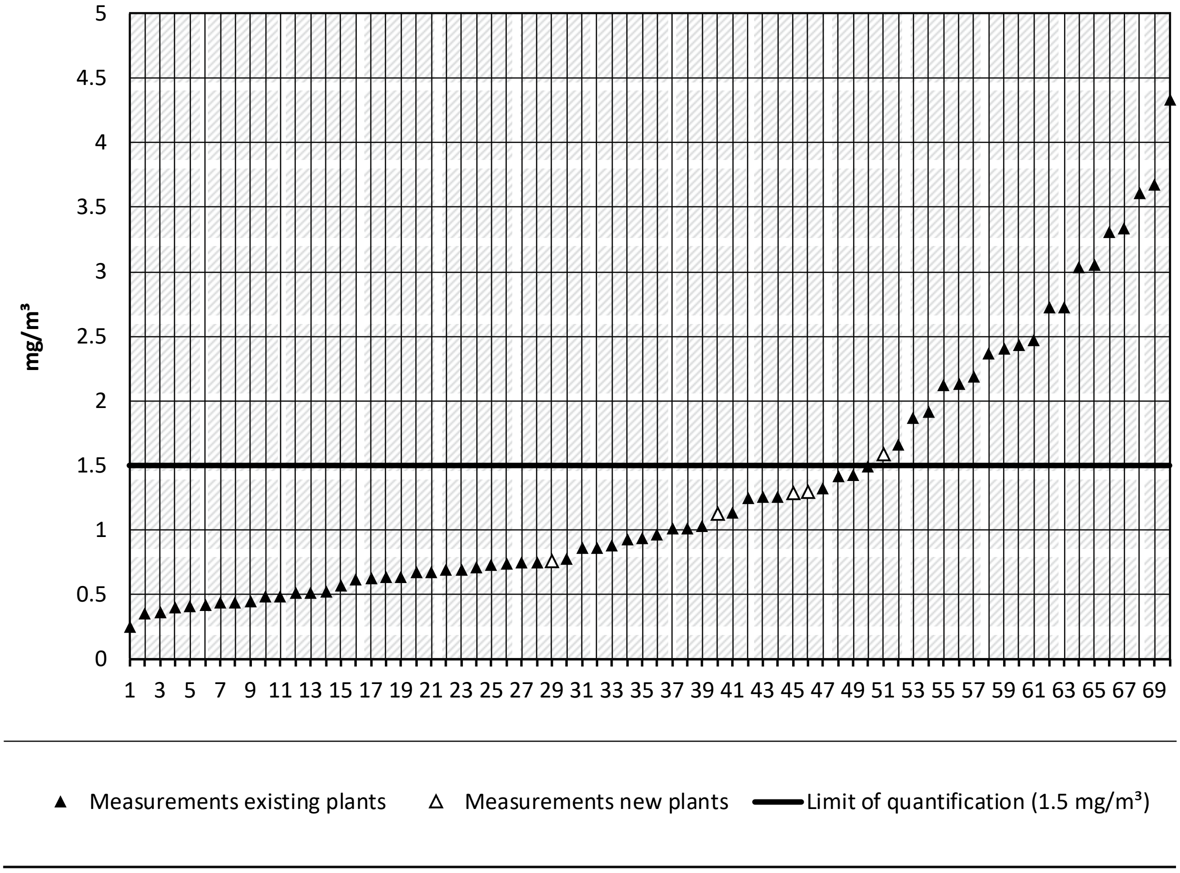
Figure 23: TOC measured values - natural gas plants (logarithmic; standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

Figure 24: TOC measured values - natural gas plants (excluding two highest values; standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Without two highest values
Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

For the correlations of TOC with methane see chapter 3.6.2 (page 116) and of TOC to carbon monoxide see chapter 3.6.3 (page 119).

When determining emission factors for TOC (see chapter 2), the two particularly high values from natural gas plants were not included in the calculation as they have a significant impact on the mean value and it was felt that, given the small number of measured values, it cannot be assumed that the emission values are representative of the overall spectrum of plants (for values that were excluded when calculating the emission factor, see the data marked in bold in Table 82).

3.4.6 Methane

Methane emissions are caused by incomplete combustion of the fuel, especially when natural gas is used. Incomplete combustion is mainly caused by sub-optimal burner settings, and also during ignition, especially when cycling at low loads.

The 28 measurements of methane at fuel oil plants resulted in emission values between 0.26 and 2.8 mg/Nm³. With 22 values, the majority (79 %) were below the limit of quantification (1.5 mg/Nm³); six values were between 1.5 and 2.8 mg/Nm³. (Figure 25)

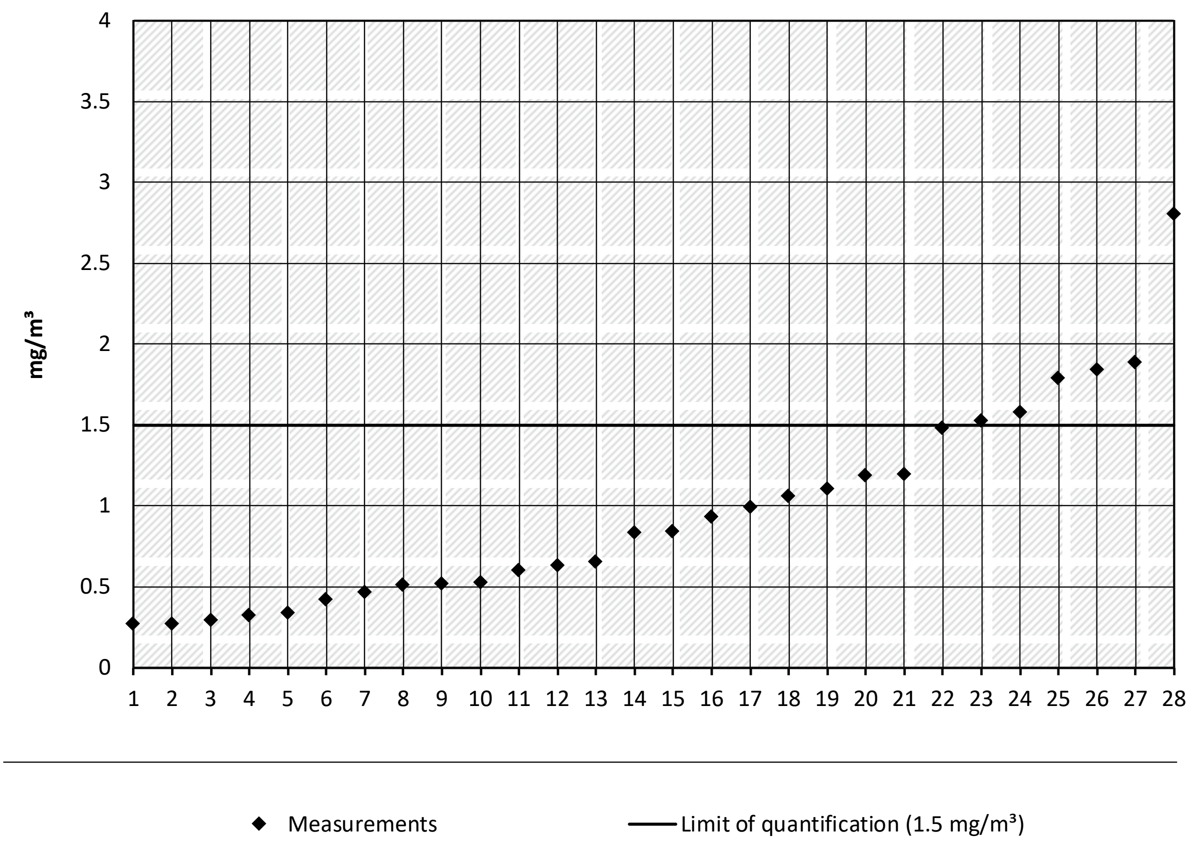
The highest value (2.8 mg/Nm³) was measured on a plant installed in 1994. The measurement was associated with heavy cycling and an average load of only 10 %. However, both the carbon monoxide value (3.8 mg/Nm³) and the smoke number (0.23) were low.

At the second highest methane value (1.9 mg/Nm³), an increased CO value (9.1 mg/Nm³) was also measured, which indicates a suboptimal burner setting. The plant was installed in 1991; the mean load was 40 % during the measurement.

The plant with the third-highest methane value (1.8 mg/Nm³) has a high CO value (32 mg/Nm³), a particularly high dust value (2.5 mg/Nm³) and a relatively high smoke number (0.89), so that a sub-optimal burner setting can be assumed. The plant was installed in 1991; the average load during the measurement was 30 %.

For the correlation of methane with other parameters, see chapter 3.6.2 (page 116) and on carbon monoxide see chapter 3.6.4 (page 122).

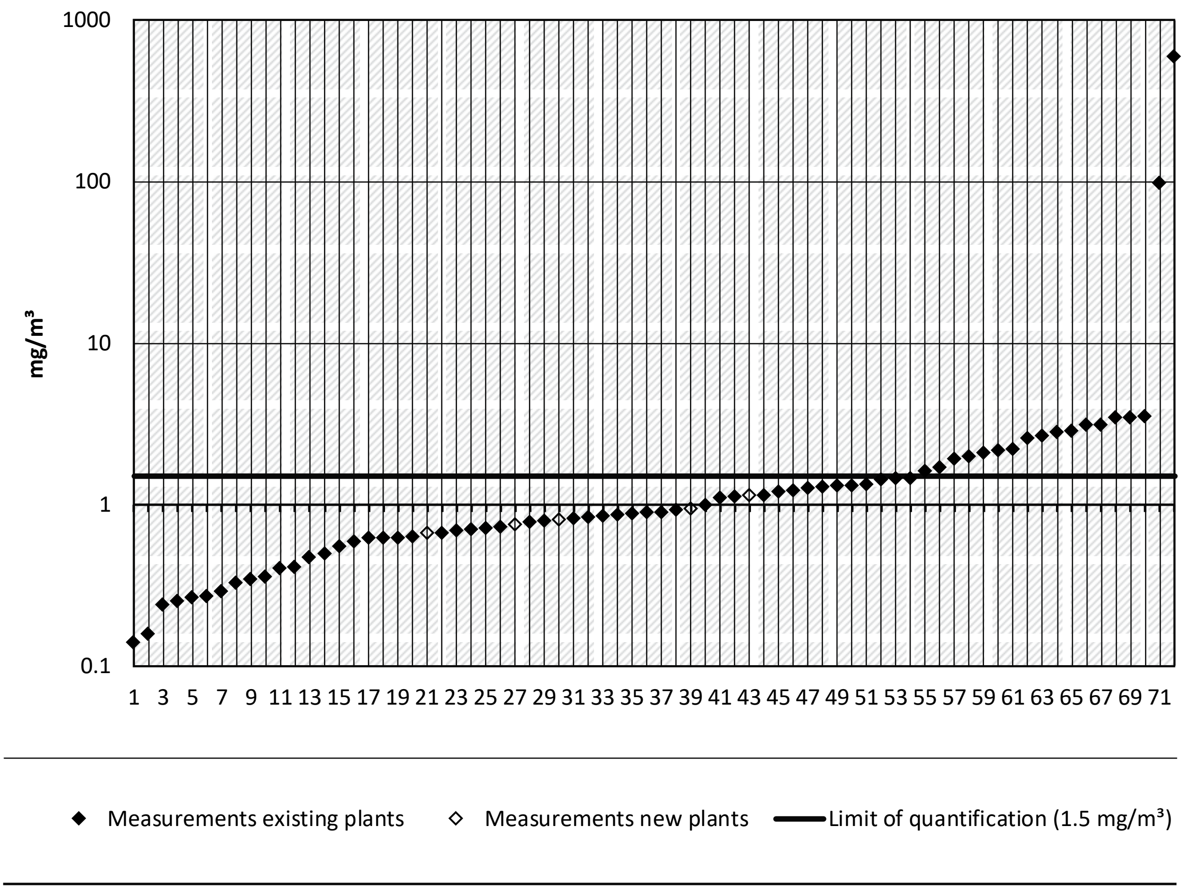
Figure 25: Methane measured values - fuel oil plants (standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Source: own figure (Ökopol)

The 72 measurements of methane at natural gas plants resulted in emission values between 0.14 and 603 mg/Nm³. The majority of the 54 values (75 %) were below the limit of quantification (1.5 mg/Nm³). Apart from two particularly high values (98/603 mg/Nm³), all other values were below 4 mg/Nm³. (Figure 26 and Figure 27 excluding the two highest values).

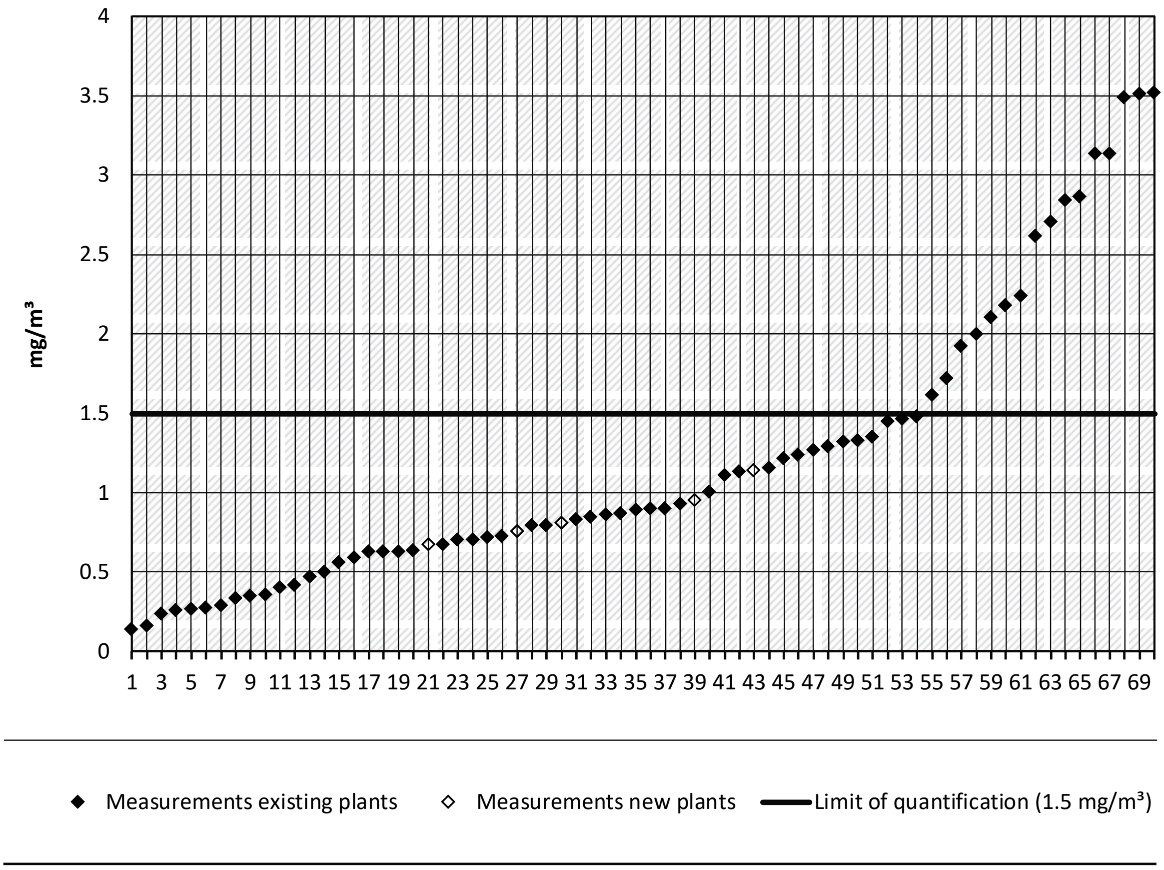
Figure 26: Methane measured values - natural gas plants (logarithmic; standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

Figure 27: Methane measured values - natural gas plants (without two highest values; standardised, 3 % reference oxygen content, average of three measurements, each usually 30 minutes)



Without two highest values
Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

When determining emission factors for methane (see chapter 2), the two particularly high values from natural gas plants were not included in the calculation, as they have a significant impact on the mean value and it was felt that, given the small number of measured values, it cannot be assumed that the emission values are representative of the overall spectrum of plants (for values that were excluded when calculating the emission factor, see the data marked in bold in Table 82).

3.4.7 NMVOC

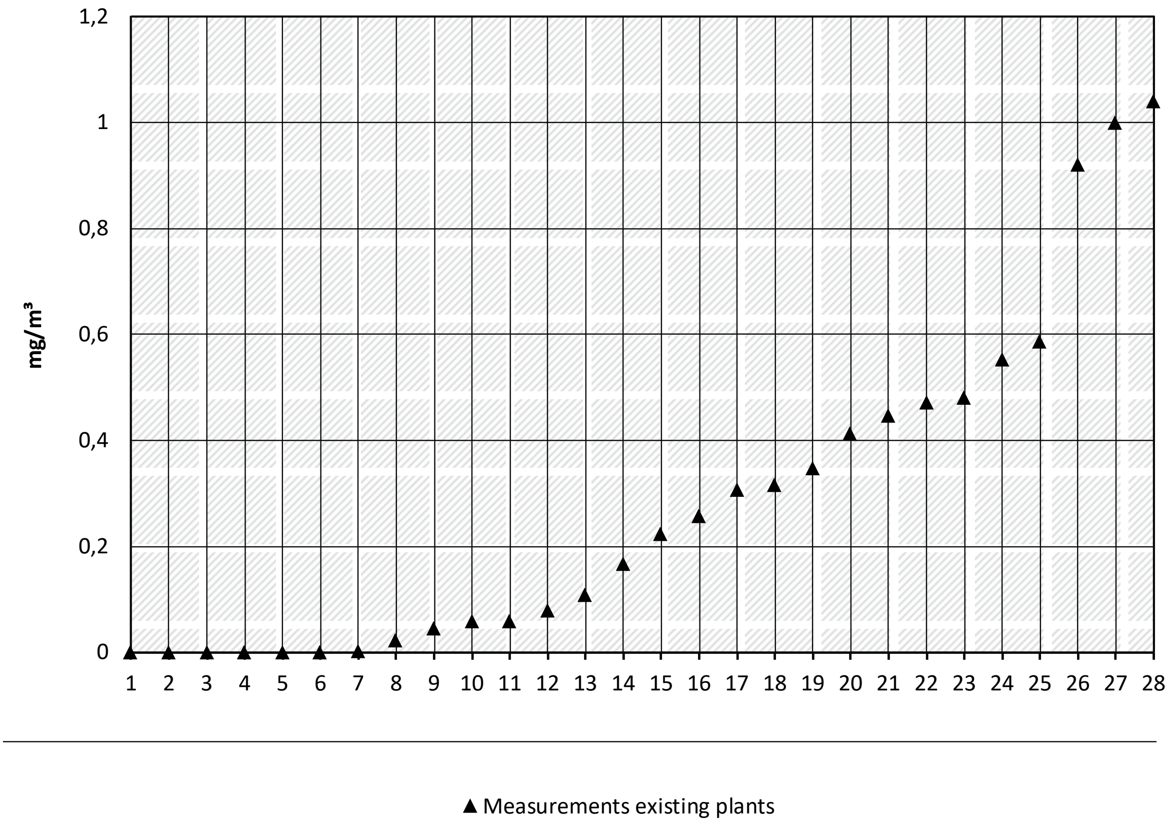
The 28 results for NMVOCs of fuel oil plants were calculated by subtracting the carbon content of the methane measurement from the value of the TOC measurement. A response factor for conversion to the organic compounds was not available.

The NMVOC values of the 28 measurements on fuel oil plants calculated as carbon content are between 0.0 and 1.04 mg C/Nm^3 (five negative values between -0.05 and -0.41 mg C/Nm^3 were set to zero). If the limit of quantification for TOC is used, all values are below this limit of quantification (1.5 mg/Nm^3). (Figure 28)

The NMVOC values of the 72 measurements on natural gas plants, calculated as carbon content, resulted in emission values between 0.0 and 141 mg C/Nm³ (seven negative values from -0.013 to -0.764 mg C/Nm³ were set to zero). Apart from two particularly high values (19/142 mg C/Nm³) and two further values around 1.7 mg C/Nm³, all values (96 %) are below the limit of quantification (1.5 mg/Nm³). (Figure 29 and Figure 30 without the two highest values)

The highest measured values correspond to the highest measured values for methane (see analysis of the measured values in the previous chapter).

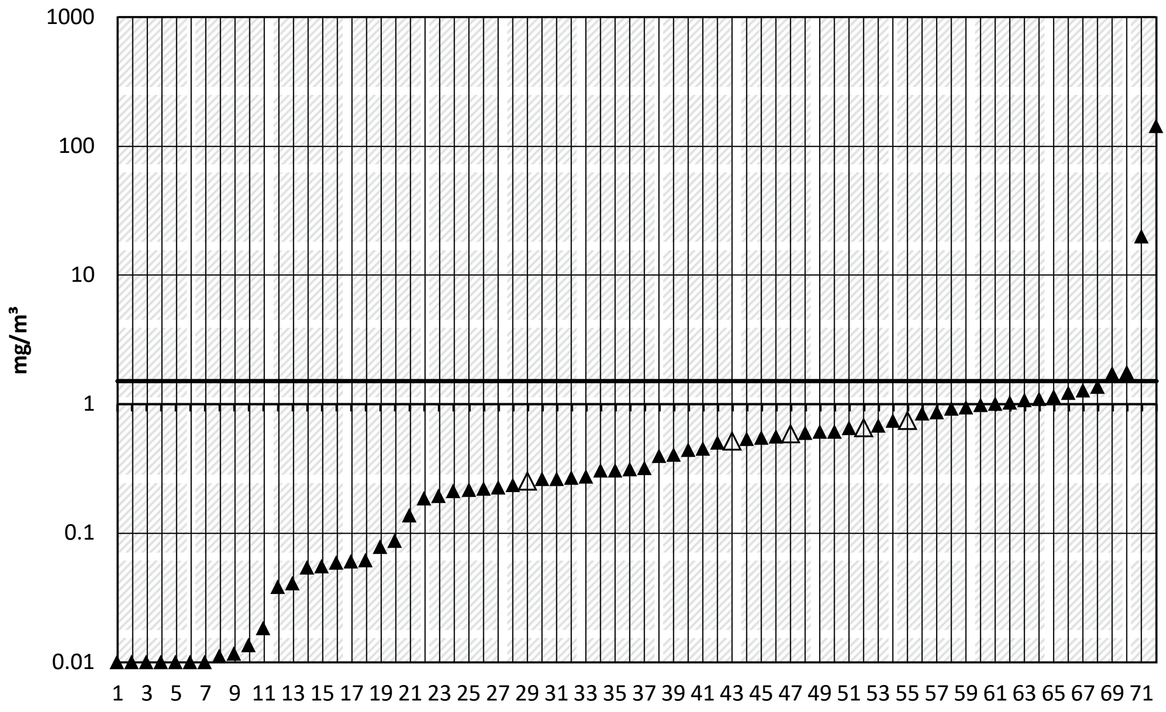
Figure 28: NMVOC calculated values - fuel oil plants (calculated from TOC and methane; standardised, 3 % reference oxygen content, average value from three measurements, each usually 30 minutes)



Negative values are plotted with zero
Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

Figure 29: NMVOC calculated values - natural gas plants (calculated from TOC and methane; logarithmic; standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



▲ Measurements existing plants

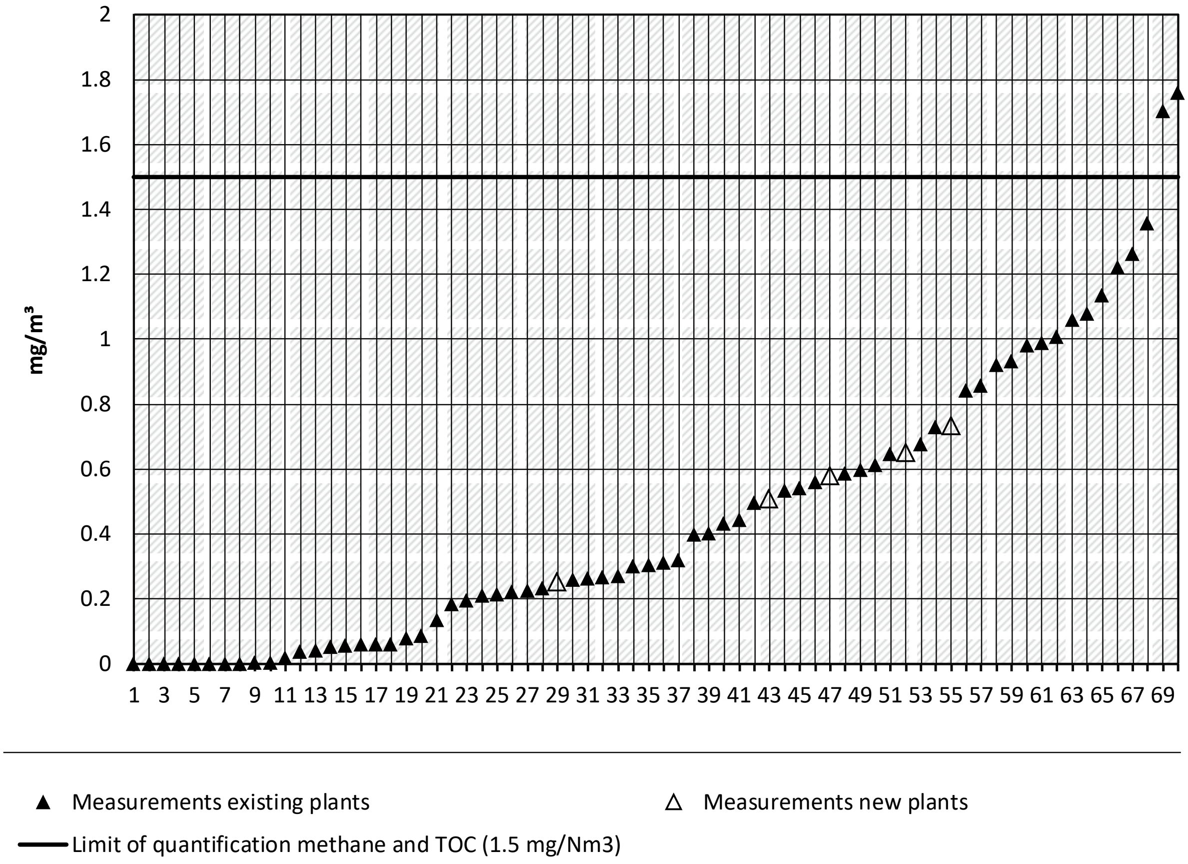
△ Measurements new plants

Limit of quantification methane and TOC (1.5 mg/Nm3)

Negative values were set as zero
Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

Figure 30: NMVOC calculated values - natural gas plants (calculated from TOC and methane; without two highest values; standardised, 3 % reference oxygen content, average of three measurements, usually 30 minutes each)



Without two highest values
Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

The emission values for NMVOC were determined by subtracting the carbon content of each methane measurement value from the corresponding TOC measurement value. Measured methane and TOC values below the limit of quantification were considered with half the limit of quantification (1.5 mg/Nm³). Two particularly high values from natural gas plants were not used, as their representativeness is not assured. The resulting NMVOC emission values for the calculation of the emission factor were 0 mg/Nm³ for all measurements of fuel oil and natural gas plants (see chapter 2).

3.5 Measurement results - maxima in comparison with limit values

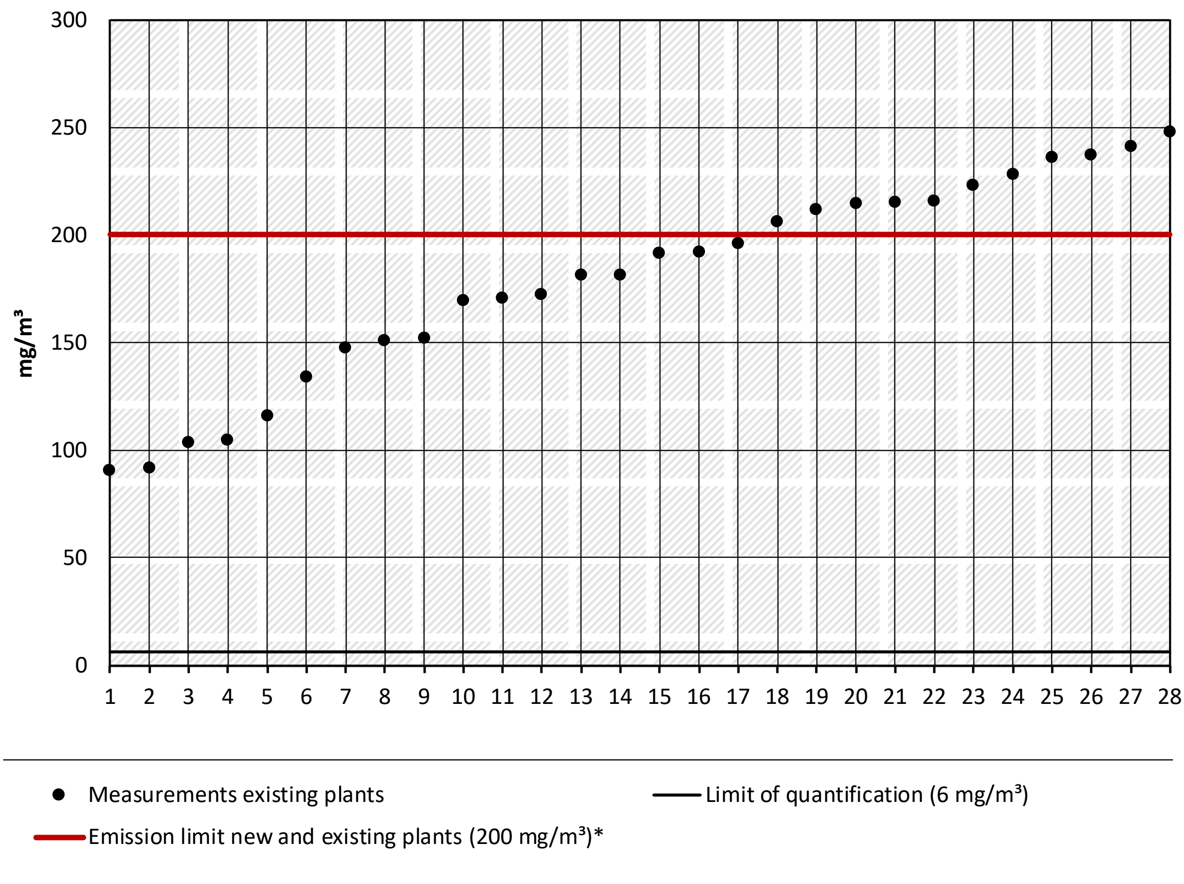
In this chapter, the maxima of the three single measurements are presented in figures, with the measurement uncertainty being added to each maximum, as required in the 44th BImSchV (2019) for compliance check with the limit values. All maxima values and maxima with measurement uncertainty added can be found in tabular form in appendix E.

3.5.1 Nitrogen oxides maxima plus measurement uncertainty

The measurement uncertainty for the nitrogen oxides measurement was 8 %. To check compliance with limit values the measurement uncertainty is added to the maxima values of nitrogen oxides, as required by the 44th BImSchV (2019). The resulting values for fuel oil plants are shown in Figure 31, and the values for natural gas plants in Figure 32.

New fuel oil plants are allowed to emit a maximum of 200 mg/Nm³ NO_x. For existing plants (installed before 20 December 2018), this limit value will apply from 1 January 2025 (44th BImSchV 2019). Until then, the 1st BImSchV (2010) applies, requiring a type test of the plant that must prove compliance with a NO_x emission of 185 mg/kWh. The requirement coming into force from 2025 was not met by eleven of the 28 measured fuel oil plants (39 %).

Figure 31: Nitrogen oxides maxima plus measurement uncertainty (8 %) compared with limit values - fuel oil plants (3 % reference oxygen content, average value over usually 30 minutes)



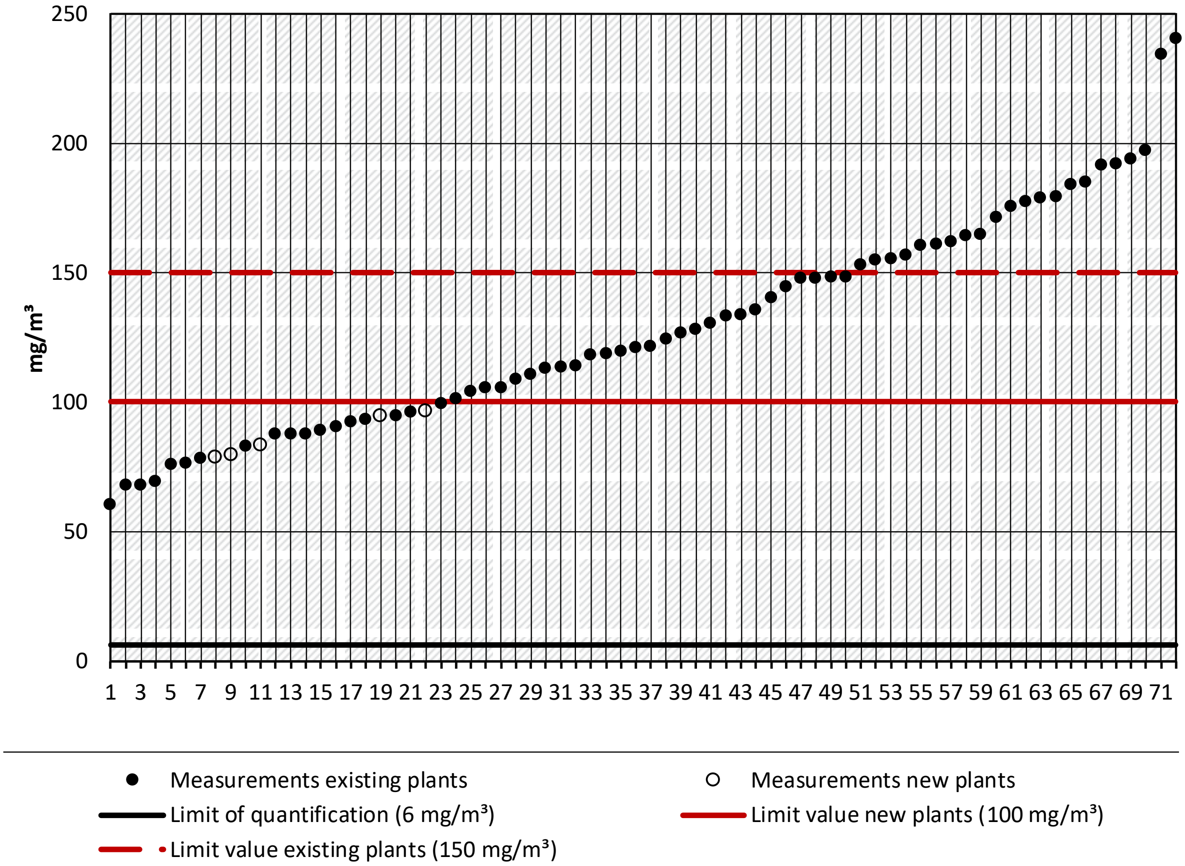
Measurement uncertainty NOx: 8 %
Existing plants started operation before 20 December 2018.
* Limit value for existing plants in force from 1.1.2025

Source: own figure (Ökopol).

New natural gas plants (installed from 20 December 2018) may emit a maximum of 100 mg/Nm³. For existing natural gas plants (installed before 20 December 2018), a limit value of 150 mg/Nm³ will apply from 1 January 2025. (44th BImSchV 2019) Until then, according to the 1st BImSchV (2010), a type test of the plant must prove that the NO_x emissions comply with 120 mg/kWh.

In the case of natural gas plants, 22 of the 67 measured existing natural gas plants did not meet the future requirements (33 %). All five measured new natural gas plants (installed from 20 December 2018, shown as a circle in the figure) complied with the current limit value for new plants; two plants, however, fell just short of the limit value. (Figure 32)

Figure 32: Nitrogen oxides maxima plus measurement uncertainty (8 %) compared with limit values - natural gas plants (standardised, 3 % reference oxygen content, average value over usually 30 minutes)



Measurement uncertainty NOx: 8 %
Existing plants started operation from 20 December 2018
For existing plants the limit value is required from 1.1.2025.

Source: own figure (Ökopol)

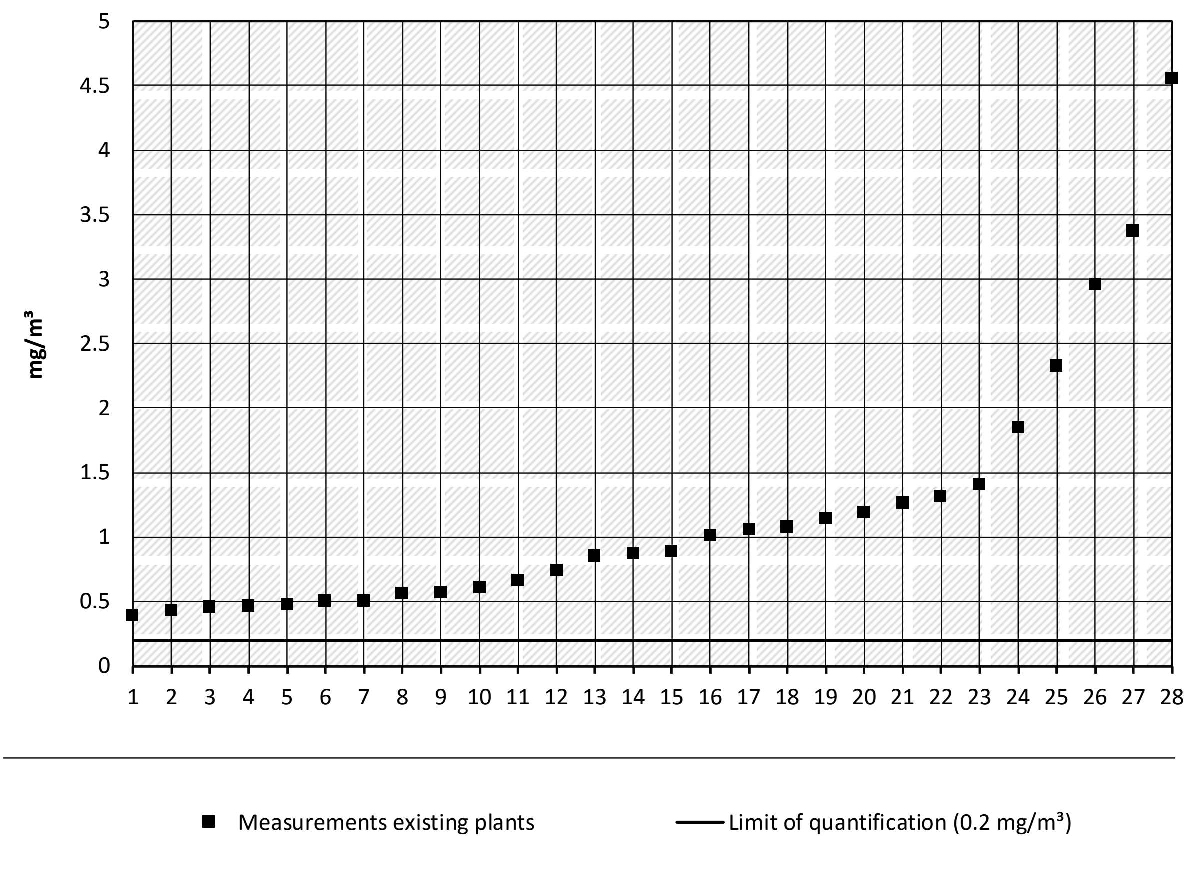
3.5.2 Dust maxima plus measurement uncertainty

The measurement uncertainty for the dust measurement was 0.3 mg/Nm³. In the figures below the measurement uncertainty is added to the maxima of the dust measurement values. Figure 33 shows the resulting values for fuel oil plants; Figure 34 shows the resulting values for natural gas plants. The 44th BImSchV (2019) does not include limit values for dust emissions.

As described in chapter 3.4.2 the measurements on fuel oil plants with the highest dust values took place, with one exception, at a particularly low load; the load during measurement of the dust maxima was (descending from the highest value) 31/74/30/40/20 %.

The maximum values of natural gas plants were measured only in three cases at relatively low loads (descending from the highest value: 100/90/95/50/65/87/60/74 % of the nominal load). As described in chapter 3.4.2 there were unfavourable measurement conditions in some cases; some measurements were also realized during operations with interrupted combustion caused by insufficient heat demand.

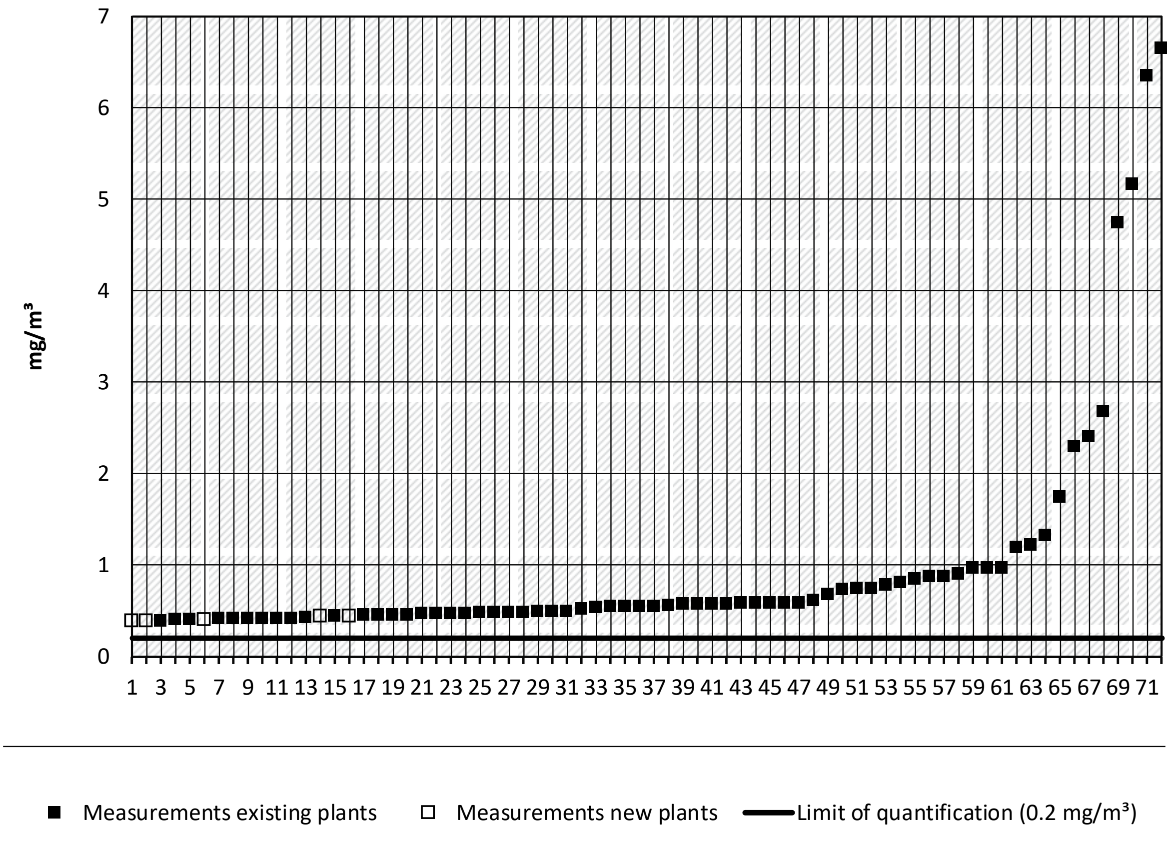
Figure 33: Dust maxima plus measurement uncertainty (0.3 mg/m³) - fuel oil plants (standardised, 3 % reference oxygen content, average value over usually 30 minutes; no limit value requirements)



Measurement uncertainty dust: 0.3 mg/m3
Existing plants started operation from 20 December 2018

Source: own figure (Ökopol)

Figure 34: Dust maxima plus measurement uncertainty (0.3 mg/m³) - natural gas combustion (standardised, 3 % reference oxygen content, average value over usually 30 minutes; no limit value requirements)



Measurement uncertainty dust: 0.3 mg/m3
Existing plants started operation before 18 December 2018

Source: own figure (Ökopol)

3.5.3 Smoke number maxima

Figure 35 shows the measured smoke number maxima. The uncertainty of the smoke number measurement was 16 %. However, the measurement uncertainty is not added when comparing with the limit value, as rounding is allowed to check compliance with the limit value. This means that a measured value of up to 1.49 complies e.g. to the limit value of 1. (VDI 2066-8 1995)

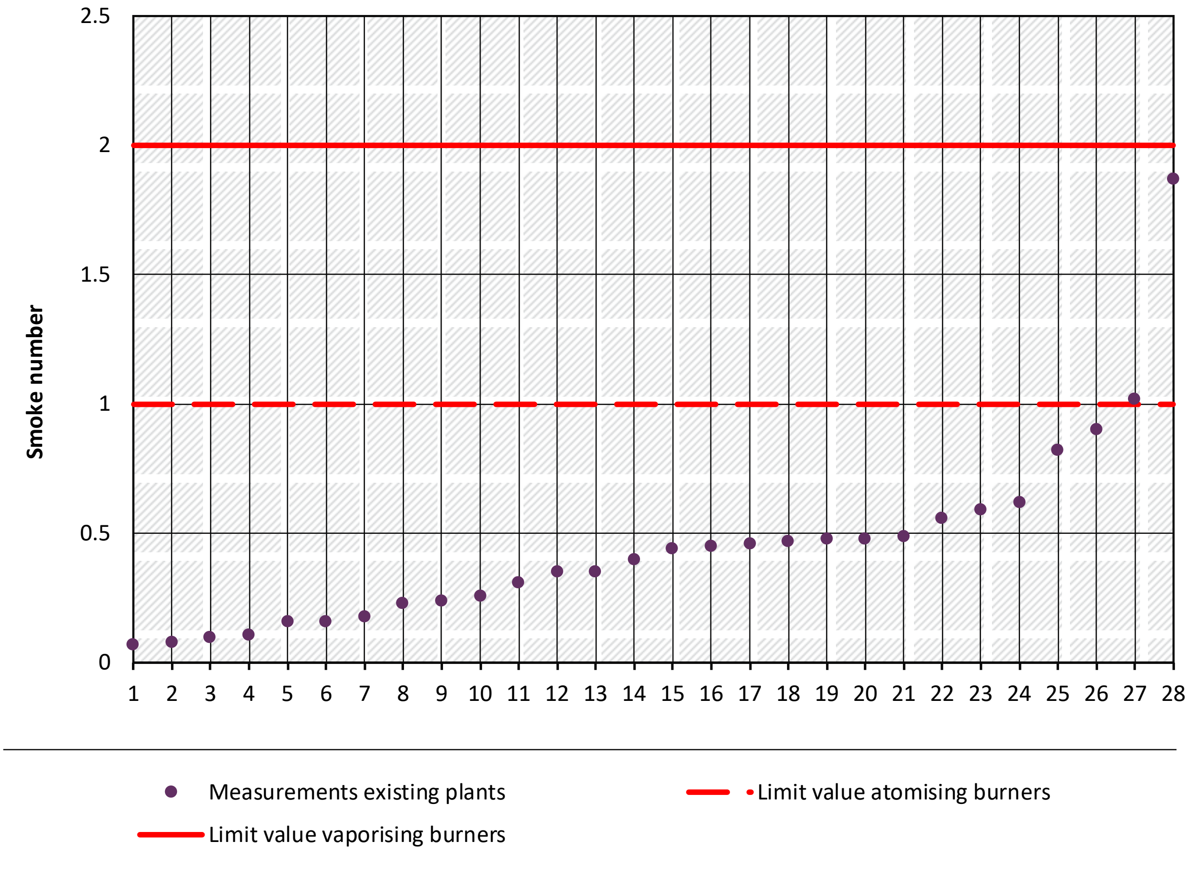
From 1 January 2025, existing fuel oil combustion plants must comply with a smoke number of 1 for atomising burners and a smoke number of 2 for vaporising burners (44th BImSchV 2019). Only atomising burners were measured during the measurements.

The requirements were not met by one (3.6 %) of the 28 measured fuel oil combustion plants, all operating with atomizing burners and classified as existing plants due to their installation before 20 December 2018.

The plant not meeting the limit value was installed in 1993. During the measurement of the relatively high smoke number of 1.87 it was operated at 20 % load only. In parallel we measured also a relatively high CO value of 31 mg/Nm³ and a relatively high dust value of 1.5 mg/Nm³. These results indicate a suboptimal combustion. During this fuel oil operation, an increase of soot on the measurement filters was recorded as the measurement period progressed. According to the operator, the load during the measurement did not correspond to the usual operating mode (the plant is in operation only at peak load or during emergencies).

During a transitional period until 31 December 2024 for atomising burners a limit value of 2 instead of 1 is in force for plants installed before 1 October 1988 and to plants installed in one of the five eastern federal states before 3 October 1990 (see § 39 (3) 44th BImSchV 2019).

Figure 35: Smoke number maxima without addition of measurement uncertainty in comparison with limit values - fuel oil plants (standardised, 3 % reference oxygen content, average value over usually 30 minutes)



Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

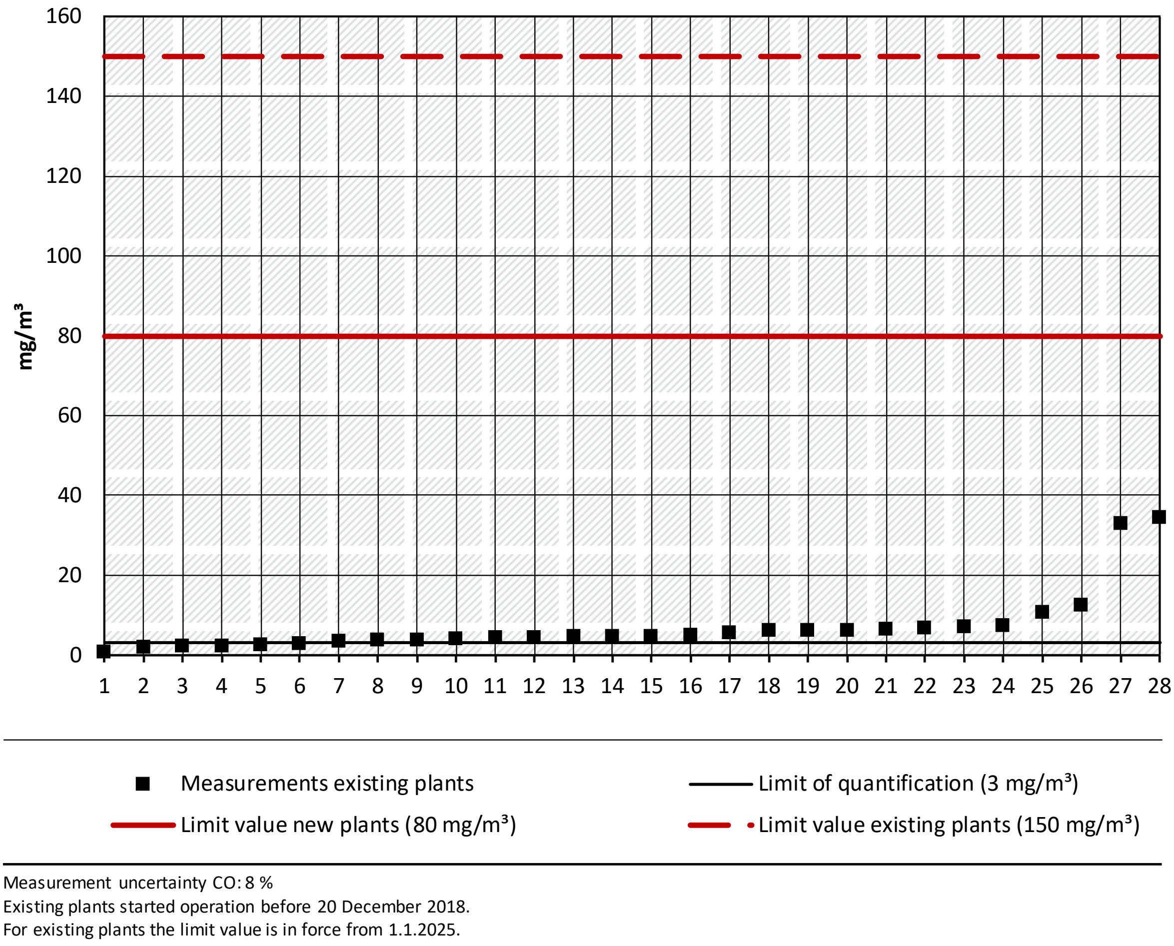
3.5.4 Carbon monoxide maxima plus measurement uncertainty

The measurement uncertainty for the carbon monoxide was 8 %. The maximum values with measurement uncertainty added, as required by the 44th BImSchV to comply with the limit values, are shown for fuel oil plants in Figure 36. For natural gas plants the maxima are presented in Figure 37 and also in Figure 38 but without the two highest values.

New fuel oil combustion plants are allowed to emit a maximum of 80 mg/Nm³ carbon monoxide. Existing fuel oil plants (installed from 20 December 2018) must comply with a maximum of 150 mg/Nm³ from 1 January 2025 (44th BImSchV 2019).

The requirements in force from 1 January 2025 were met by all 28 measured fuel oil plants, installed before 20 December 2018. (Figure 36)

Figure 36: Carbon monoxide maxima plus measurement uncertainty (8 %) compared with limit values - fuel oil plants (standardised, 3 % reference oxygen content, average value over usually 30 minutes)

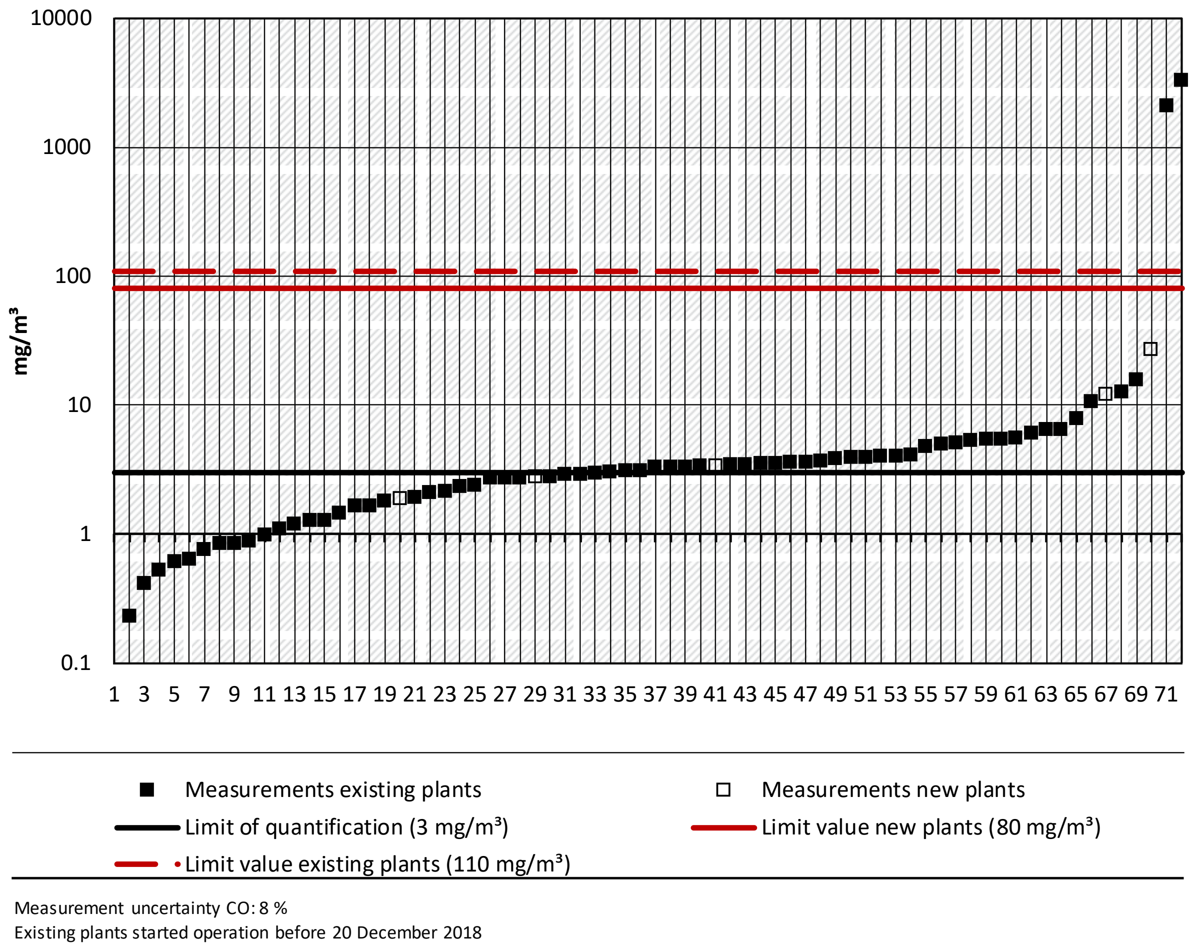


Source: own figure (Ökopol)

Existing natural gas plants must comply with a limit value of 110 mg/Nm³ from 1 January 2025, new natural gas plants 80 mg/Nm³.

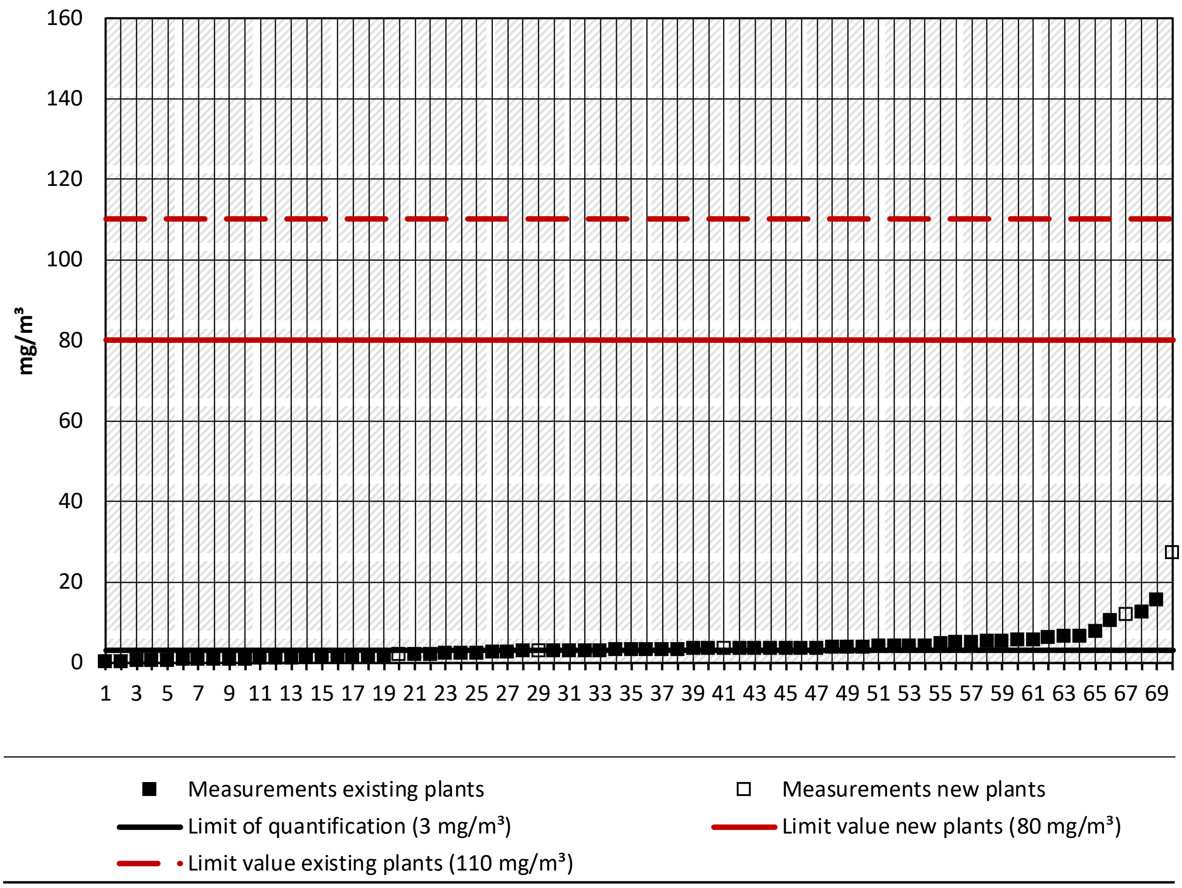
In the case of existing natural gas plants, two (3 %) of the 67 measured plants did not meet the future requirements. The five new natural gas plants measured (installed from 20 December 2019, in the figure presented as unfilled boxes) complied with the requirements. (Figure 37)

Figure 37: Carbon monoxide maxima plus measurement uncertainties (8 %) compared with limit values - natural gas plants (logarithmic; standardised, 3 % reference oxygen content, average value over usually 30 minutes)



Source: own figure (Ökopol)

Figure 38: **Carbon monoxide maxima plus measurement uncertainty (8 %) compared with limit values - natural gas plants (without two highest values; standardised, 3 % reference oxygen content, average value over usually 30 minutes)**



Without two highest values
Measurement uncertainty CO: 8 %
Existing plants started operation before 20 December 2018

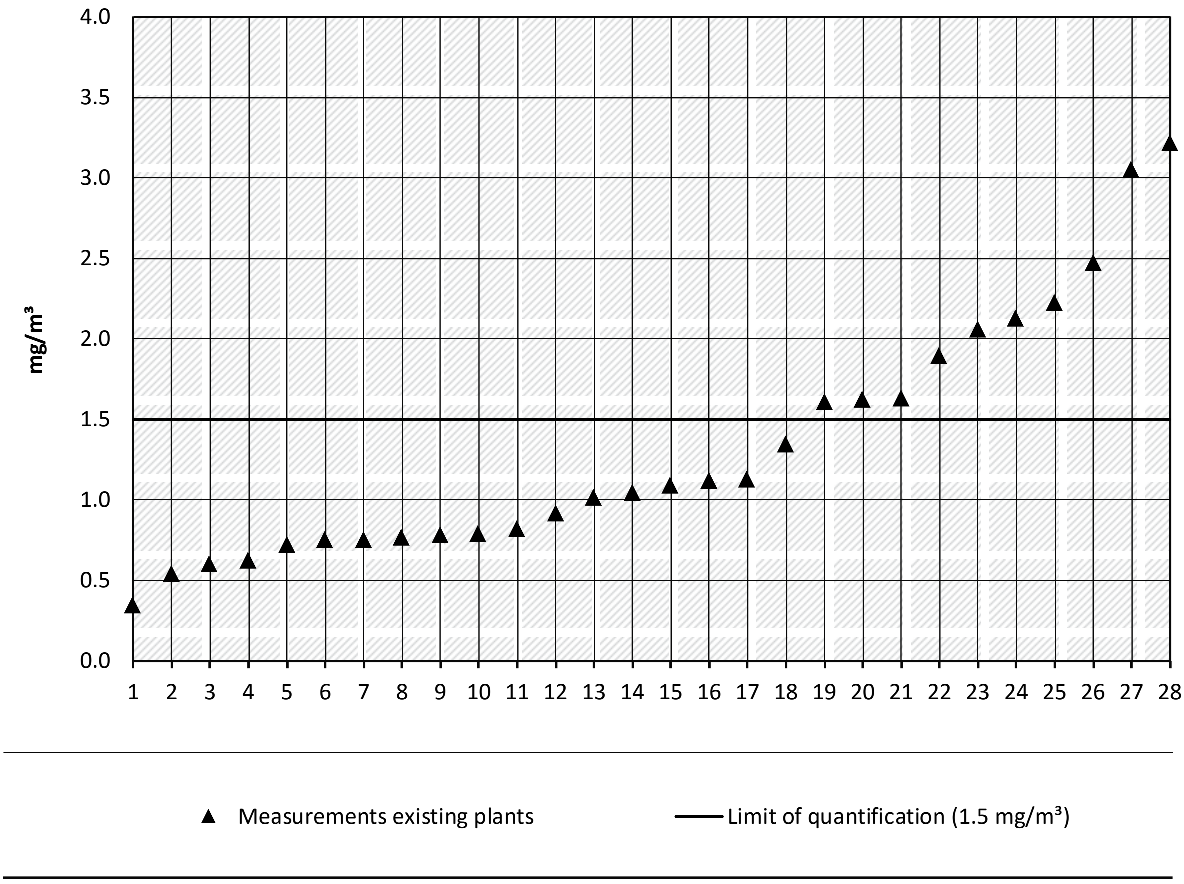
Source: own figure (Ökopol)

3.5.5 TOC maxima plus measurement uncertainty

The measurement uncertainty for the TOC measurement was 15 %. Figure 39 shows the maximum values for fuel oil plants with the measurement uncertainty added. Figure 40 presents the values for natural gas plants, and Figure 41 shows the values of natural gas plants without the two highest values.

The 44th BImSchV (2019) does not include limit values for TOC emissions.

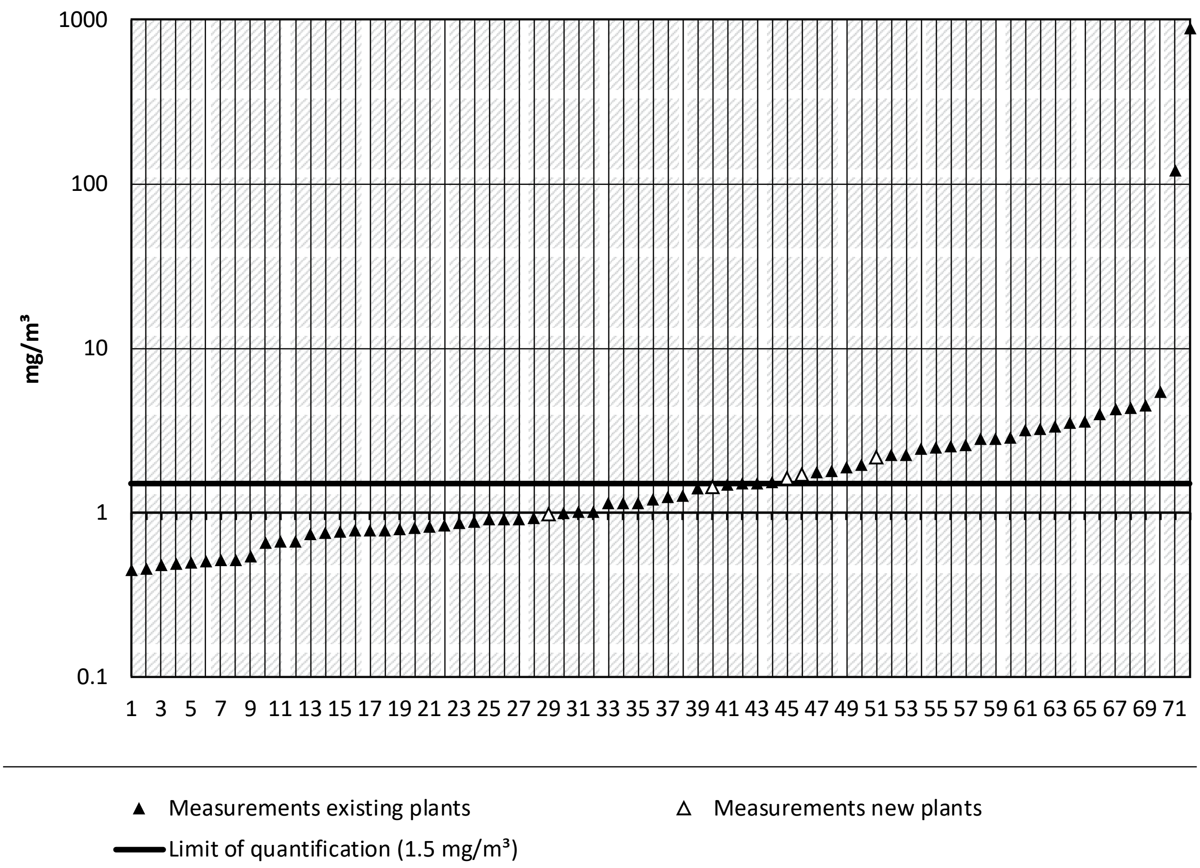
Figure 39: TOC maxima plus measurement uncertainty (15 %) - fuel oil plants (standardised, 3 % reference oxygen content, average value over usually 30 minutes; no limit value requirements)



Measurement uncertainty TOC: 15 %
Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

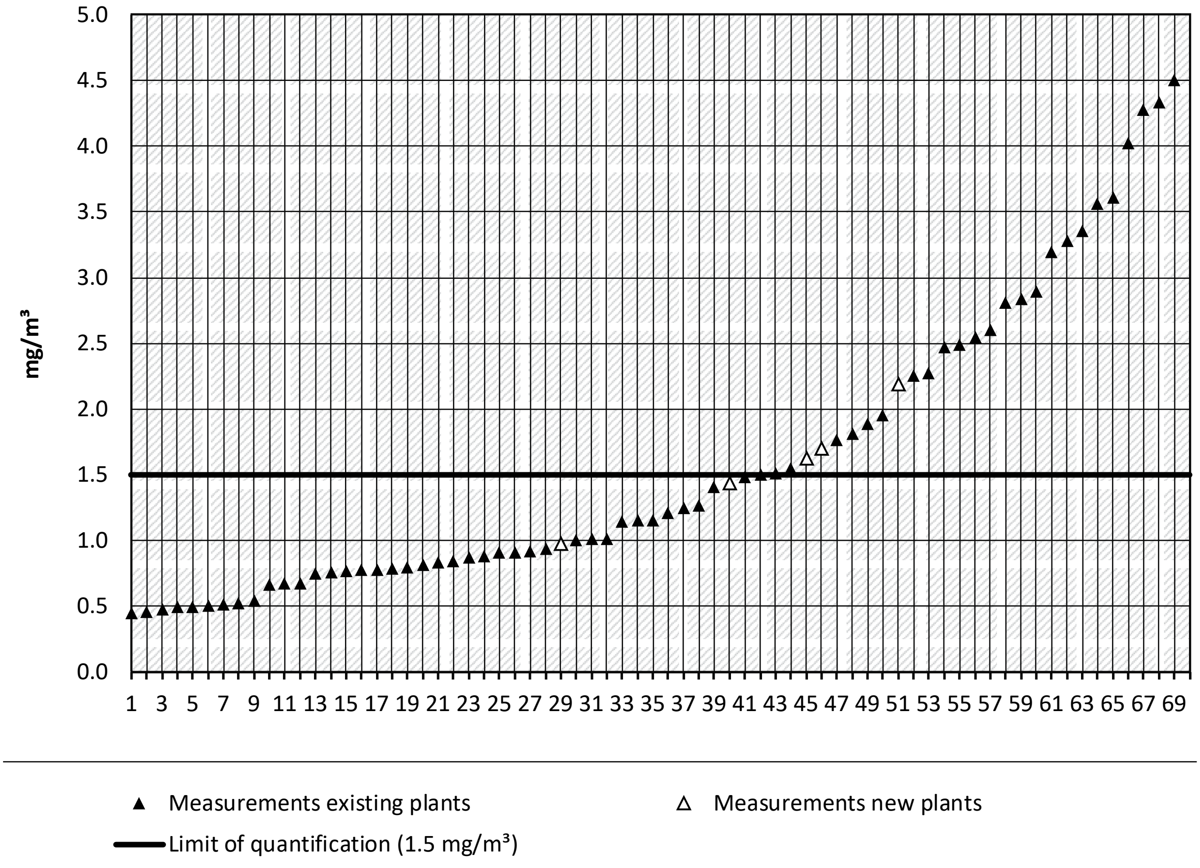
Figure 40: TOC maxima plus measurement uncertainty (15 %) - natural gas plants (logarithmic; standardised, 3 % reference oxygen content, average value over usually 30 minutes; no limit value requirements)



Measurement uncertainty TOC: 15 %
Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

Figure 41: TOC maxima plus measurement uncertainty (15 %) - natural gas plants (without two highest values; standardised, 3 % reference oxygen content, average value over usually 30 minutes; no limit value requirements)



Without two highest values
Measurement uncertainty TOC: 15 %
Existing plants started operation before 20 December 2018

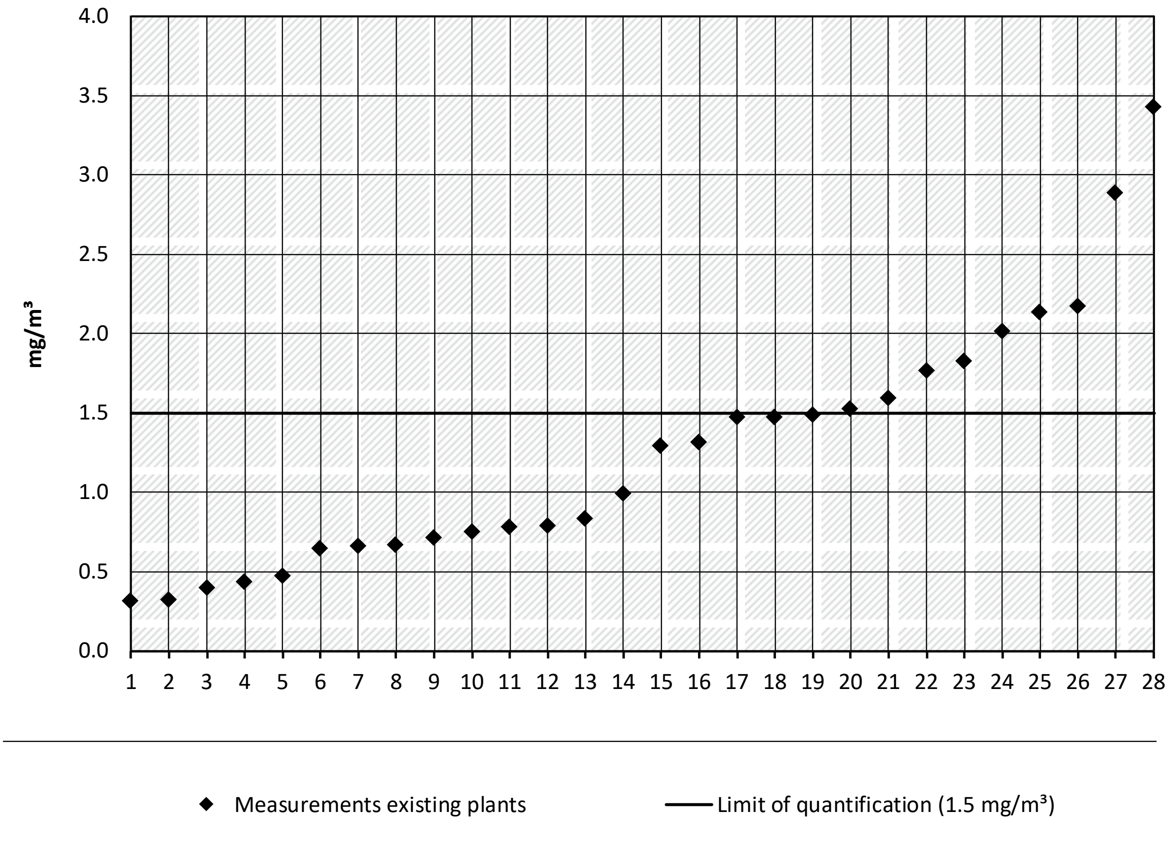
Source: own figure (Ökopol)

3.5.6 Methane maxima plus measurement uncertainty

The measurement uncertainty for the methane measurement was 18 %. Figure 42 shows the values for fuel oil combustion plants with the measurement uncertainty added to the maximum values. For natural gas plants the maximum values are presented in Figure 43 and in Figure 44 without the two highest values.

The 44th BImSchV (2019) does not include limit value for methane emissions.

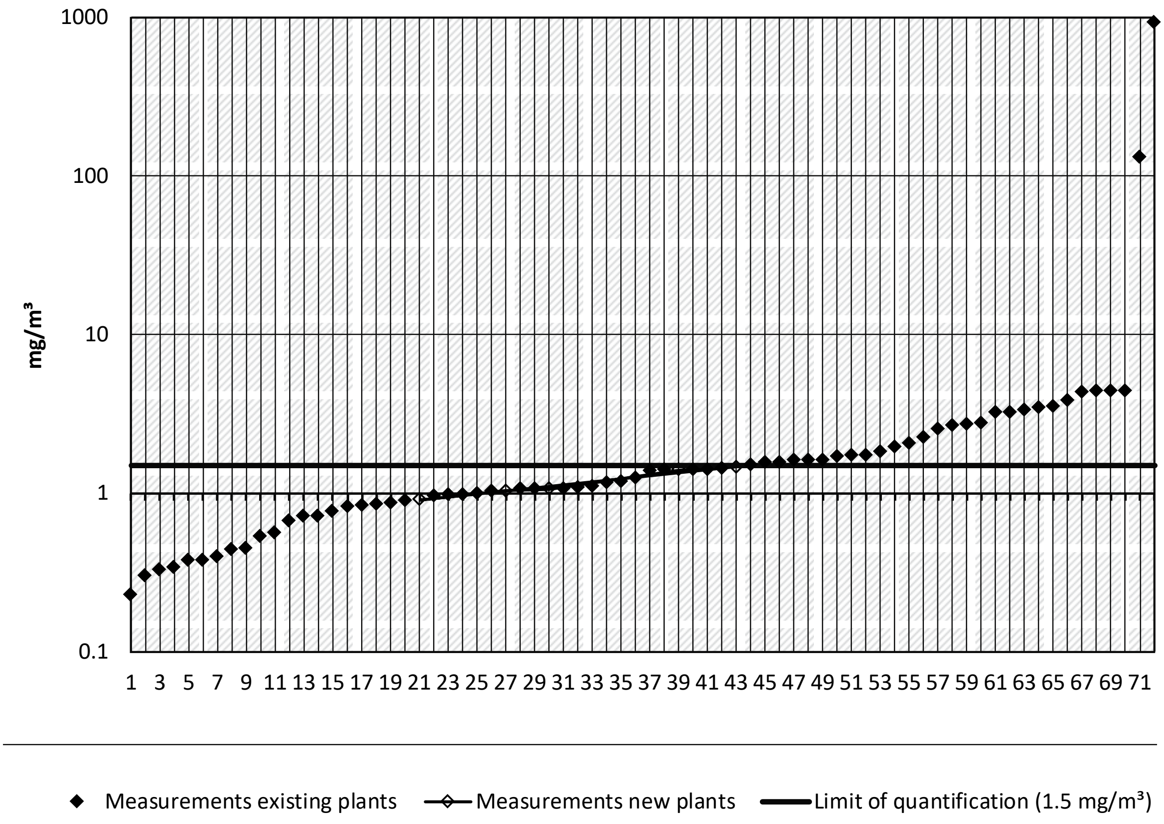
Figure 42: Methane maxima plus measurement uncertainty (18 %) - fuel oil plants (standardised, 3 % reference oxygen content, average value over usually 30 minutes; no limit value requirements)



Measurement uncertainty methane: 18 %
Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

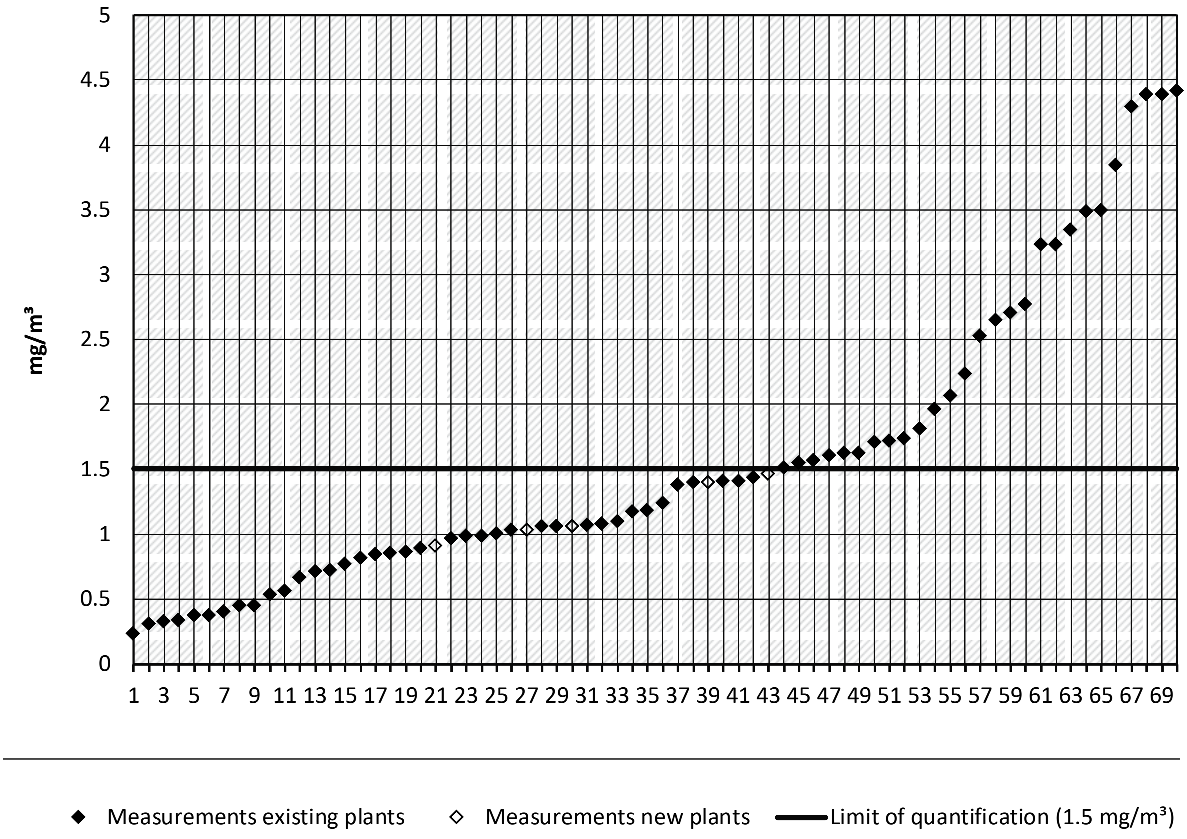
Figure 43: Methane maxima plus measurement uncertainty (18 %) - natural gas plants (standardised, 3 % reference oxygen content, average value over usually 30 minutes; no limit value requirements)



Measurement uncertainty methane: 18 %
Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

Figure 44: Methane maxima - natural gas plants (without two highest values; standardised, 3 % reference oxygen content, average value over usually 30 minutes)



Without two highest values
Measurement uncertainty methane: 18 %
Existing plants started operation before 20 December 2018

Source: own figure (Ökopol)

3.6 Measurement results - correlations

In this chapter, measurement results of different parameters are correlated if there are reasons to suspect a correlation. Only measurement results that were above the limit of quantification of the measurement method were included in the analysis.

3.6.1 Overview

The figures in Table 55 were tested for their correlation. A high correlation exists if the value is close to 1 or -1. The number of measured values that exceeded the limit of quantification and were used for the analysis is shown in brackets. In the following sections, in addition to the correlation factor in the graphs, the coefficient of determination (R^2) is also shown, which indicates a high correlation for values close to 1.

Table 55: Correlation coefficients between emission parameters

Emission parameters	Fuel oil (number of analysed values)	Natural gas (number of values)	Natural gas without highest values (number of values)
TOC / methane	1,0 (2)	1,0 (15)	0,89 (13)
TOC / CO	-0,71 (4)	0,96 (8)	0,011 (6)
CO / methane	-0,091 (6)	0,96 (9)	0,73 (7)
Smoke number / CO	0,73 (22)	(-)	(-)
Smoke number / dust	0,39 (21)	(-)	(-)
Dust / CO	0,53 (17)	0,0035 (18)	-0,33 (16)
NO_x / CO	0,077 (22)	0,18 (30)	0,14 (28)

Source: Calculation based on own measurements

The correlation coefficients determined show that

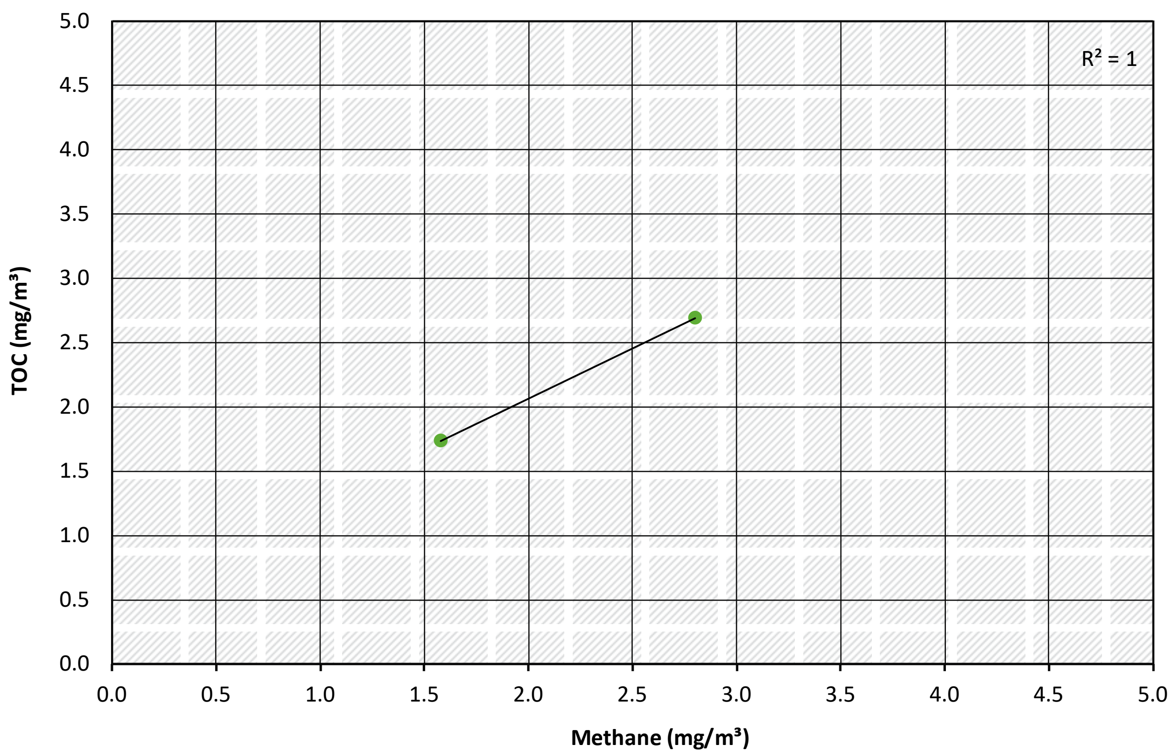
- For TOC and methane, the value for fuel oil combustion is based on only two values, resulting in a correlation coefficient of 1.
- There is a correlation between carbon monoxide and TOC and between carbon monoxide and methane in the case of natural gas combustion (coefficient 0.96), but only if the two highest values are included. The results are based on relatively few pairs of measured values.
- In the case of fuel oil combustion, the correlation between smoke number and dust is low (coefficient 0.39) and lower than the correlation between smoke number and carbon monoxide (0.73).
- There is a correlation between carbon monoxide and dust in the case of fuel oil combustion (coefficient 0.53).
- There is no correlation between nitrogen oxides and carbon monoxide for either fuel oil or natural gas combustion (correlation factors close to 0).

3.6.2 TOC and methane

It can be assumed that the emissions of total organic compounds, which were measured as TOC, consist mainly of methane, particularly in the case of natural gas combustion. The correlation was therefore analysed.

For the analysis of the correlation of TOC and methane emissions from fuel oil plants, only two measured mean values above the limit of quantification were available, of course resulting in a correlation factor of 1.0. Since only two values were available, no statement about a correlation is possible. (Figure 45)

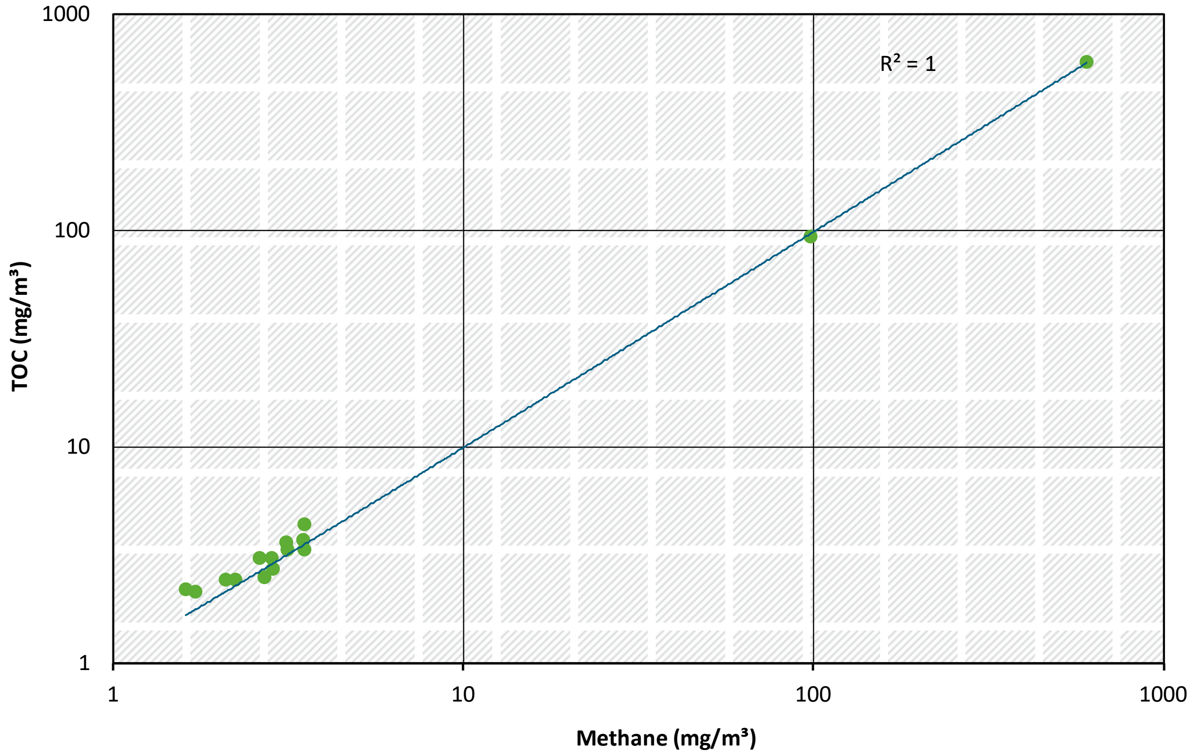
Figure 45: Correlation: TOC and methane - fuel oil plants



Source: own figure (Ökopol)

For the analysis of the correlation of TOC and methane emissions from natural gas combustion, 15 measured mean values above the limit of quantification were available. The resulting correlation factor is 1.0. This shows a high correlation and confirms the assumption that the TOC emissions from natural gas combustion consist mainly of methane. (Figure 46)

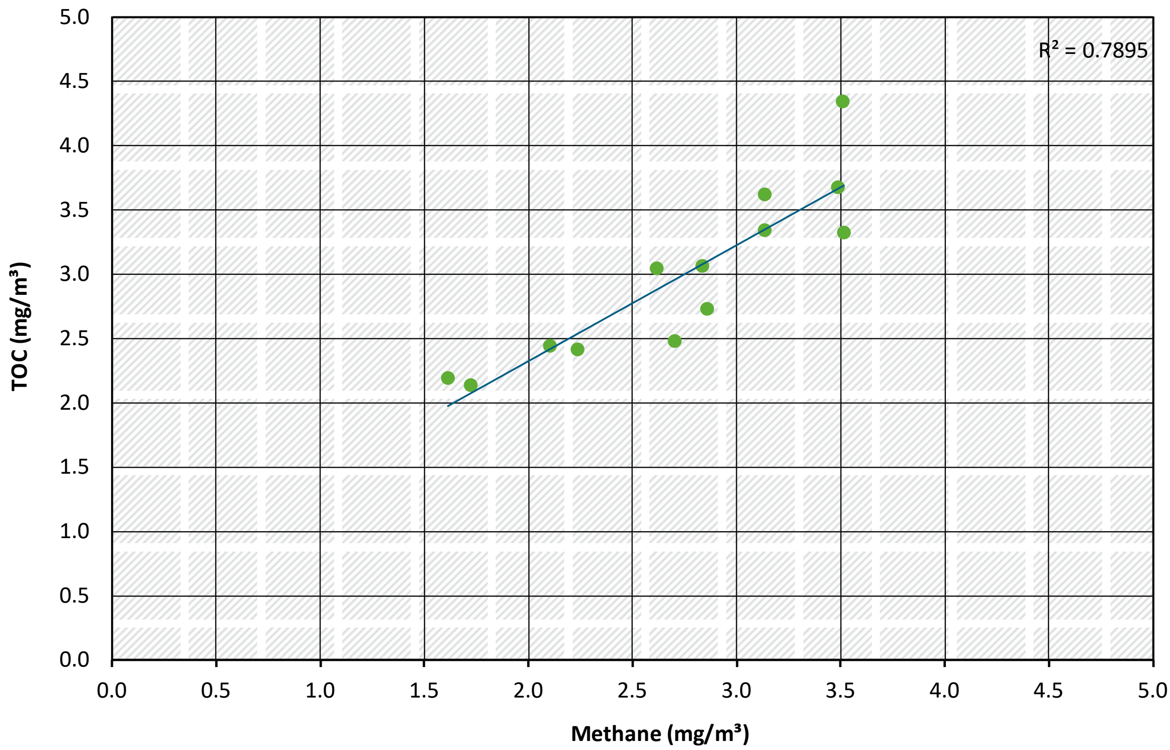
Figure 46: Correlation: TOC and methane - natural gas plants



Source: own figure (Ökopol)

If the two highest values are excluded when analysing the correlation of TOC and methane emissions from natural gas combustion due to the higher measurement uncertainty associated with them, 13 measured mean values above the limit of quantification remain. The resulting correlation factor is 0.89. This confirms the high correlation and also the assumption that the TOC emissions from natural gas combustion consist mainly of methane. (Figure 47)

Figure 47: Correlation: TOC and methane - natural gas plants (without two highest values)



Without two highest values

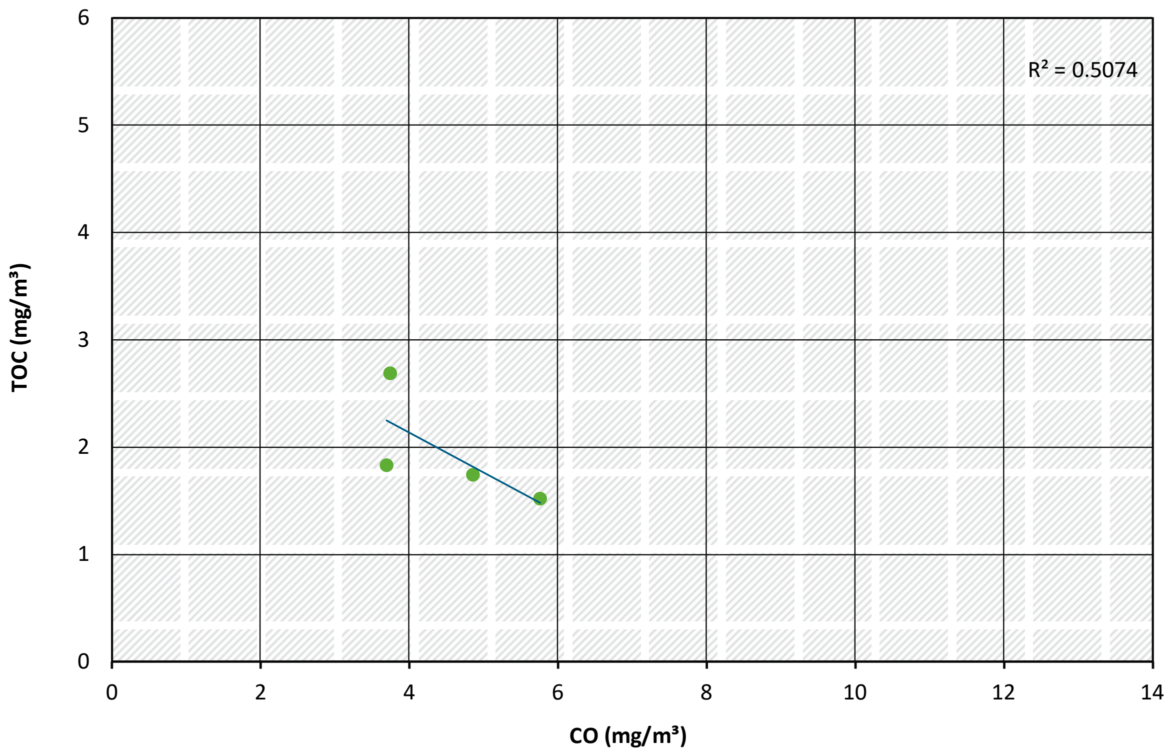
Source: own figure (Ökopol)

3.6.3 TOC and carbon monoxide

In the case of incomplete combustion, emissions of organic compounds (TOC) can also increase in addition to carbon monoxide emissions if the fuel is not completely burnt. A correlation was therefore analysed.

For the analysis of the correlation of TOC and carbon monoxide emissions from fuel oil combustion, only four measured mean values were above the limit of quantification. The resulting correlation factor is -0.71. (Figure 48)

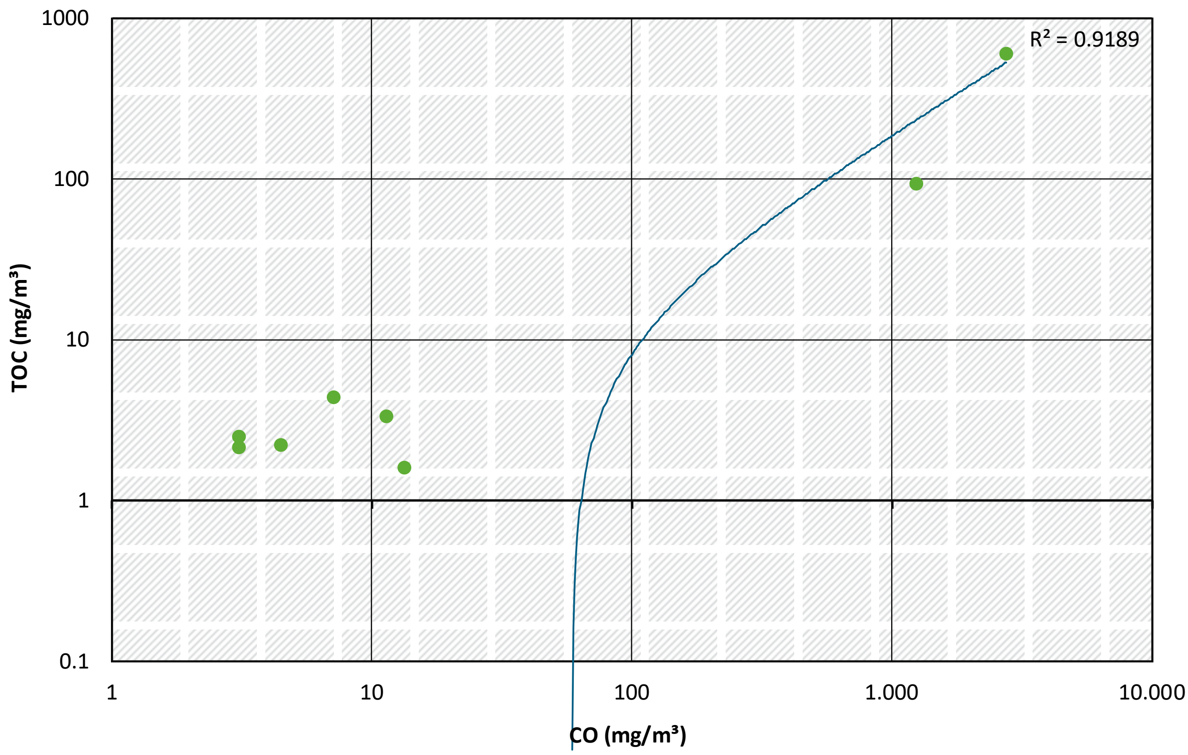
Figure 48: Correlation: TOC and carbon monoxide - fuel oil plants



Source: own figure (Ökopol)

For the analysis of the correlation of TOC and carbon monoxide emissions from natural gas combustion, eight pairs of measured values with values above the limit of quantification were available, two of which had particularly high values. The resulting correlation factor is 0.96, which indicates a high correlation. (Figure 49)

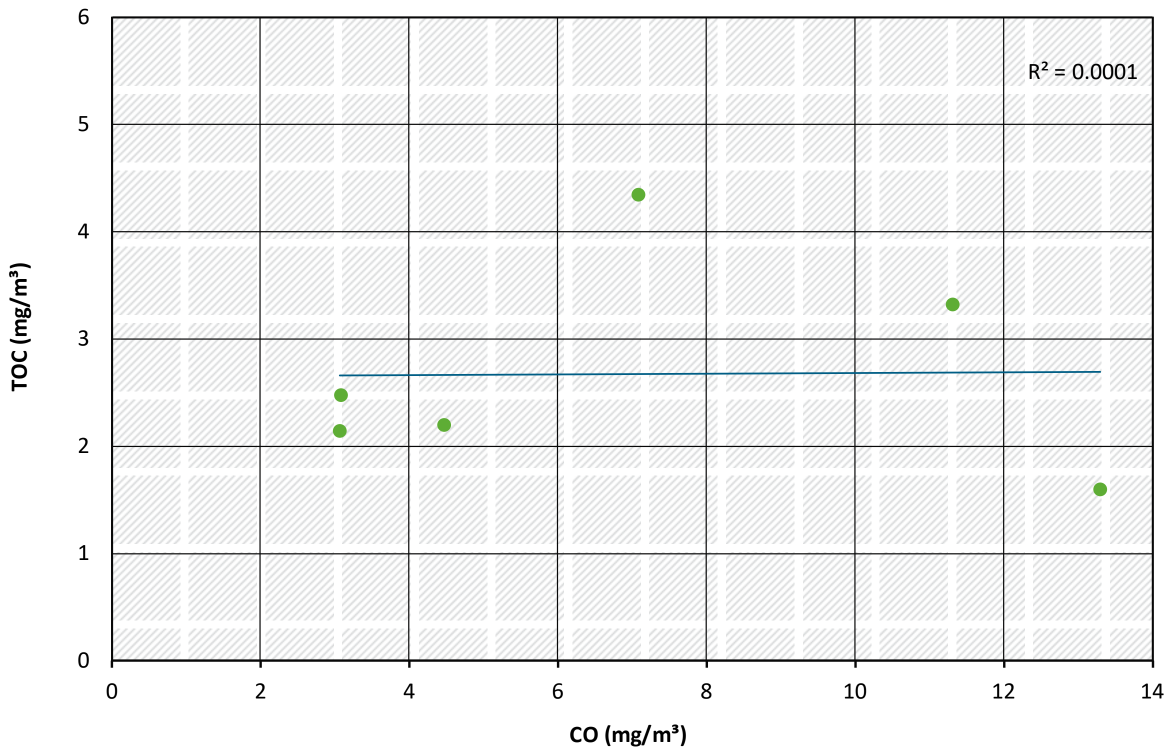
Figure 49: Correlation: TOC and carbon monoxide - natural gas plants



Source: own figure (Ökopol)

If the two highest values, which are associated with increased measurement uncertainty, are excluded, six pairs of measured values remain. Their correlation coefficient is 0.011 and indicates that there is no correlation. (Figure 50)

Figure 50: Correlation: TOC and carbon monoxide - natural gas plants (without two highest values)



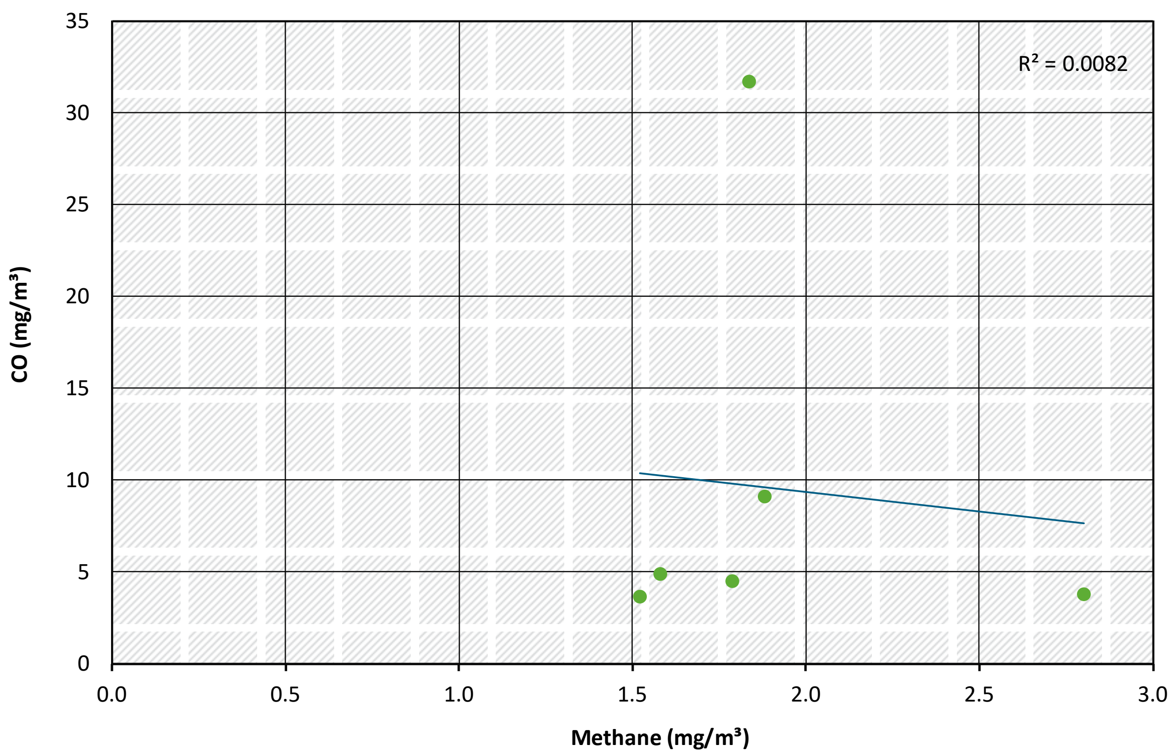
Source: own figure (Ökopol)

3.6.4 Carbon monoxide and methane

In the same way as stated above for the emissions of TOC, it is to be expected that incomplete combustion also increases the emissions of methane in addition to carbon monoxide emissions if the fuel is not completely burnt, especially in the case of natural gas combustion. A correlation was therefore analysed.

For the analysis of the correlation of carbon monoxide and methane emissions from fuel oil combustion, only six measured pairs of values above the limit of quantification were available. The resulting correlation factor is -0.091, meaning that there is no correlation. (Figure 51)

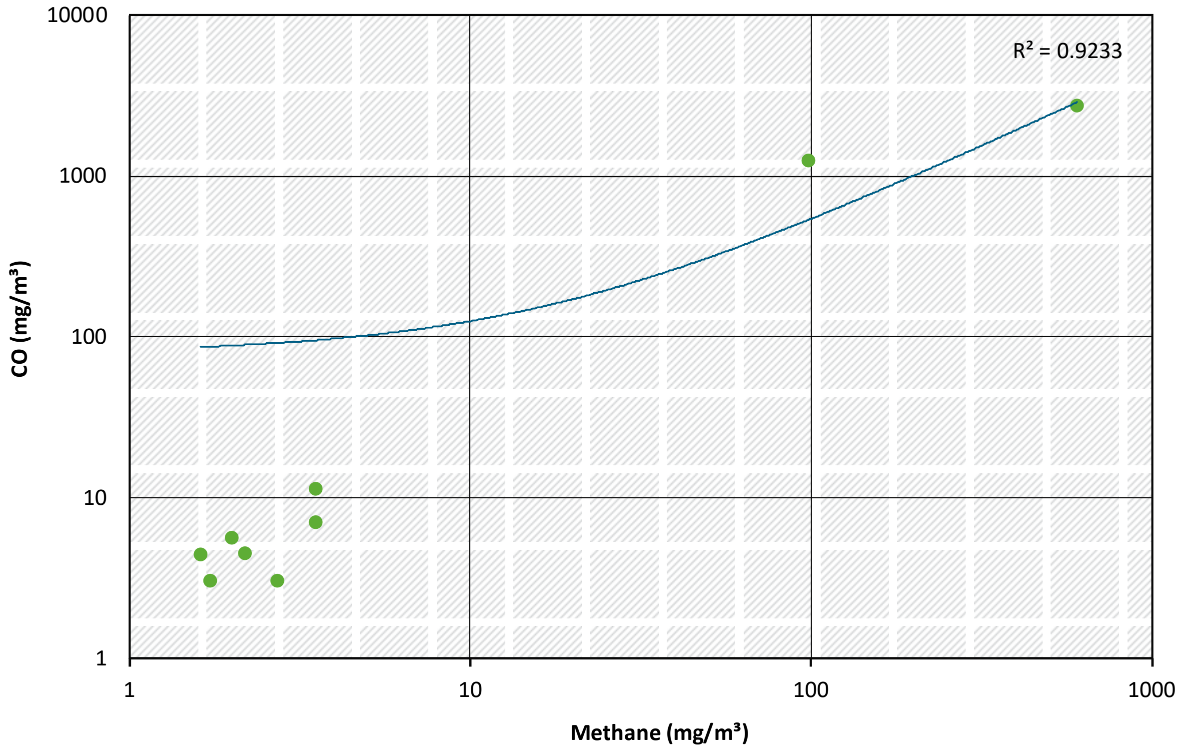
Figure 51: Correlation: Carbon monoxide and methane - fuel oil plants



Source: own figure (Ökopol)

For the correlation test of carbon monoxide and methane emissions from natural gas combustion, only nine pairs of measured values were above the limit of quantification. The resulting correlation factor is 0.96, meaning that there is a high correlation. (Figure 52)

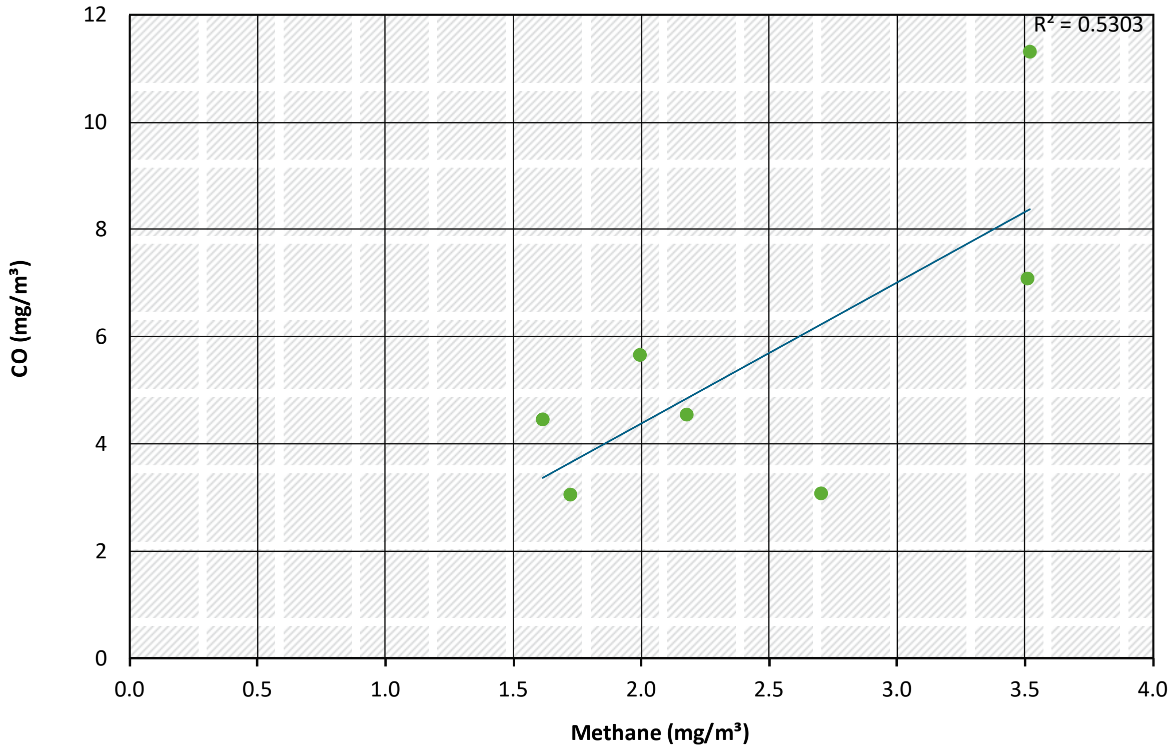
Figure 52: Correlation: Carbon monoxide and methane - natural gas plants



Source: own figure (Ökopol)

If the two highest values are excluded from the correlation test of carbon monoxide and methane emissions from natural gas combustion due to their increased measurement uncertainty, seven pairs of measured values above the limit of quantification are still available for analysis. The resulting correlation factor is 0.73, which also indicates a correlation. (Figure 53)

Figure 53: Correlation: Carbon monoxide and methane - natural gas plants (without two highest values)



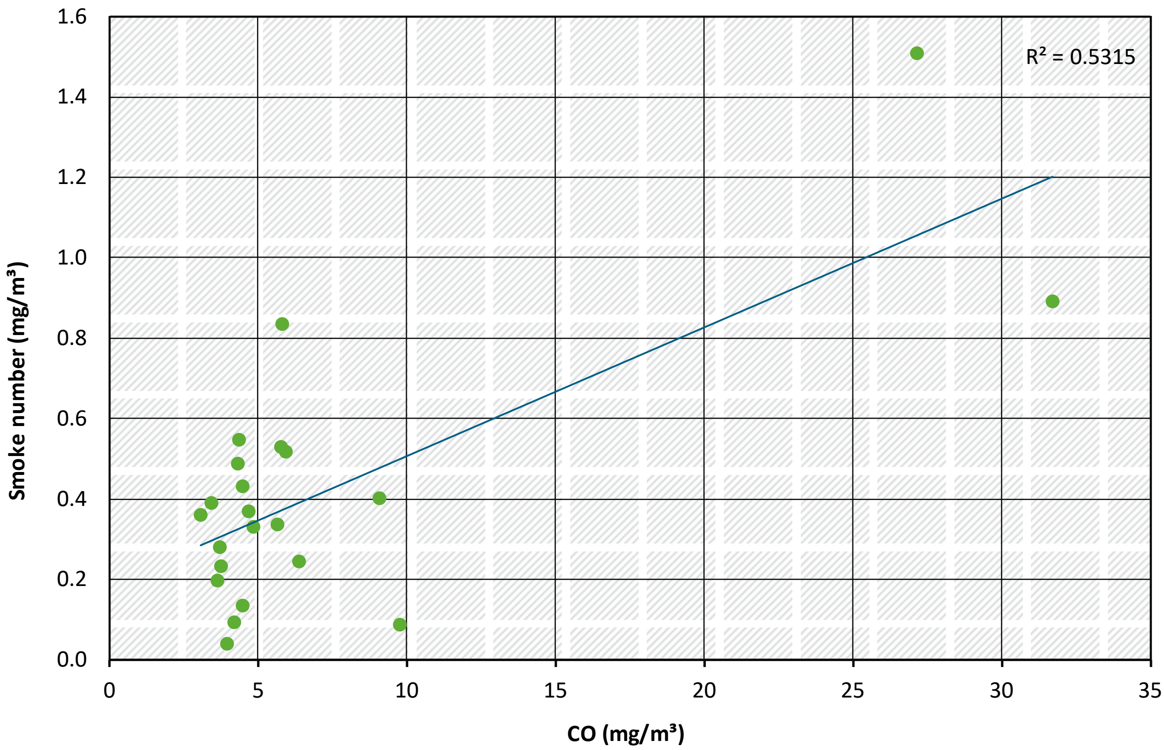
Source: own figure (Ökopol)

3.6.5 Smoke number and carbon monoxide

Since incomplete combustion can sometimes be accompanied by both soot and carbon monoxide emissions, a correlation was tested.

For the analysis of the correlation between smoke number and carbon monoxide emissions from fuel oil combustion, 22 measured pairs of values were above the limit of quantification. The resulting correlation factor is 0.73, so that a correlation can be established here. (Figure 54).

Figure 54: Correlation: Smoke number and carbon monoxide - fuel oil plants



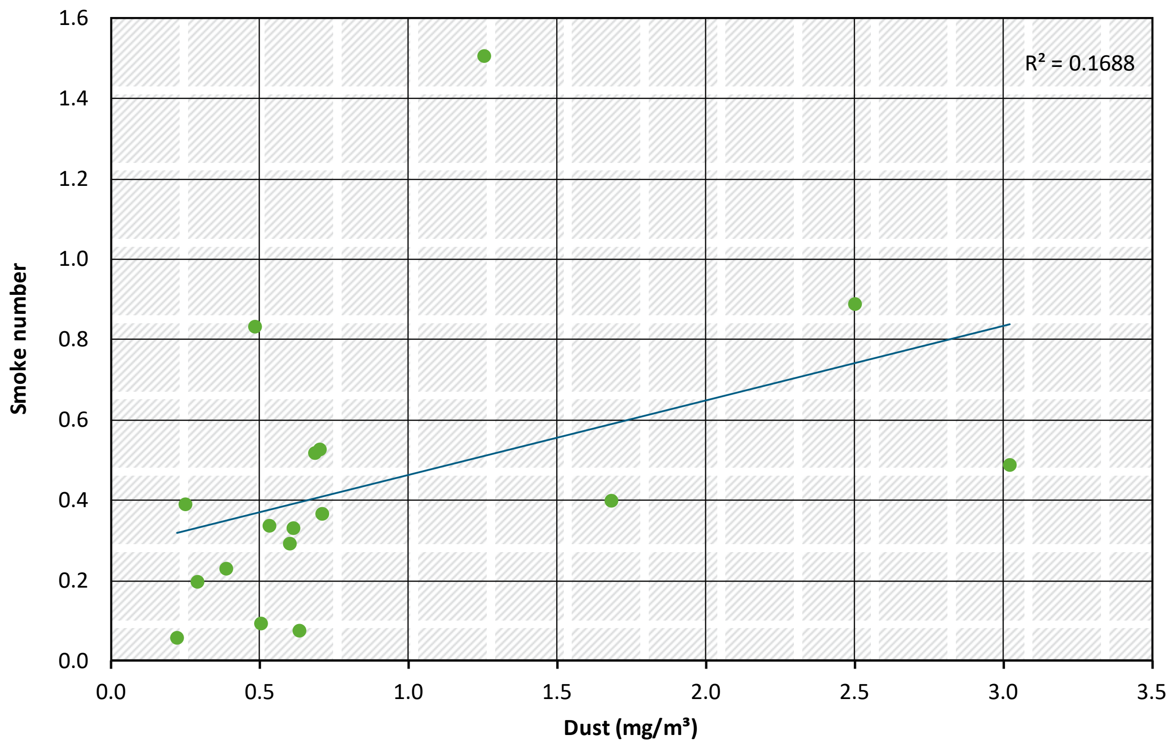
Source: own figure (Ökopol)

3.6.6 Smoke number and dust

As soot partly consists of components that are present in particulate form during dust measurement and therefore are also measured, there could be a correlation. In addition, incomplete combustion can be accompanied by both dust and soot formation.

For the analysis of the correlation of smoke number and dust concentration, 21 pairs of measured values above the limit of quantification were available from fuel oil combustion. The resulting correlation factor is 0.39, so that no correlation can be noticed. (Figure 55)

Figure 55: Correlation of smoke number and dust - fuel oil plants



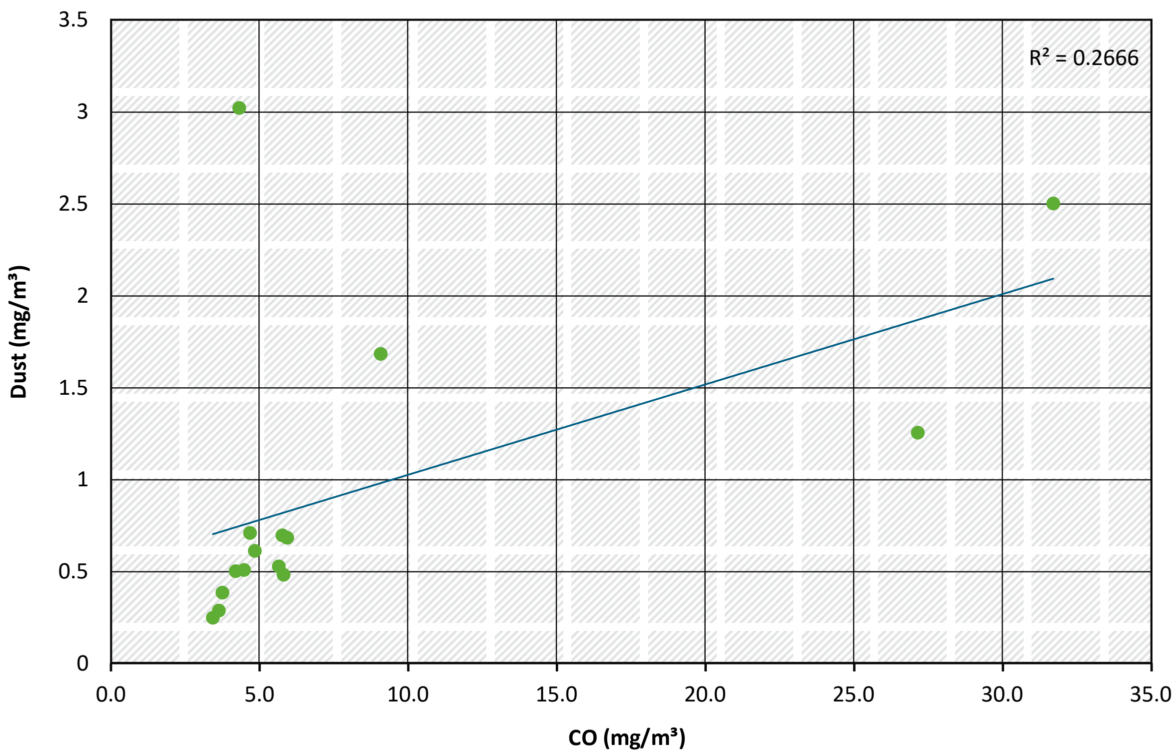
Source: own figure (Ökopol)

3.6.7 Dust and carbon monoxide

Since incomplete combustion can sometimes be accompanied by both dust and carbon monoxide emissions, a correlation was tested.

For the analysis of the correlation of dust and carbon monoxide emissions from fuel oil combustion, 17 pairs of measured values were above the limit of quantification. The resulting correlation factor is 0.53, so that a low correlation can be determined. (Figure 56)

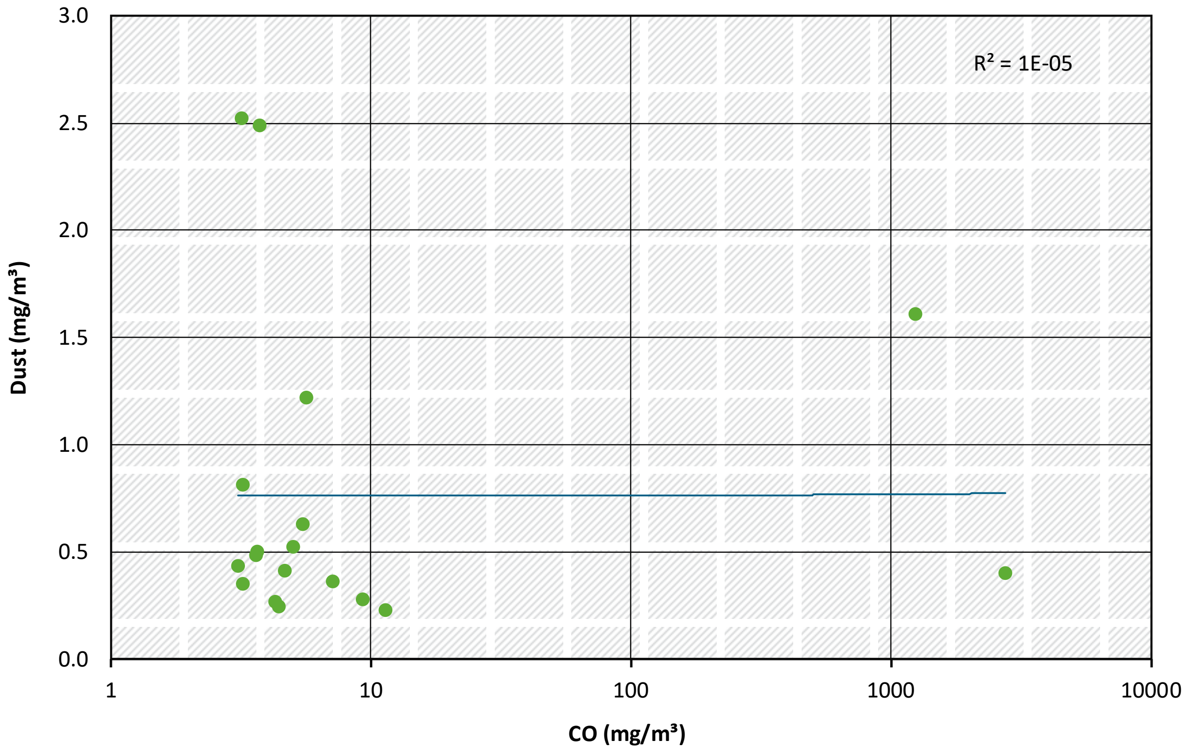
Figure 56: Correlation dust and carbon monoxide - fuel oil plants



Source: own figure (Ökopol)

For the analysis of the correlation of dust and carbon monoxide emissions from natural gas plants, 18 pairs of measured values were above the limit of quantification. The resulting correlation factor is 0.0035, so that no correlation can be determined. (Figure 57).

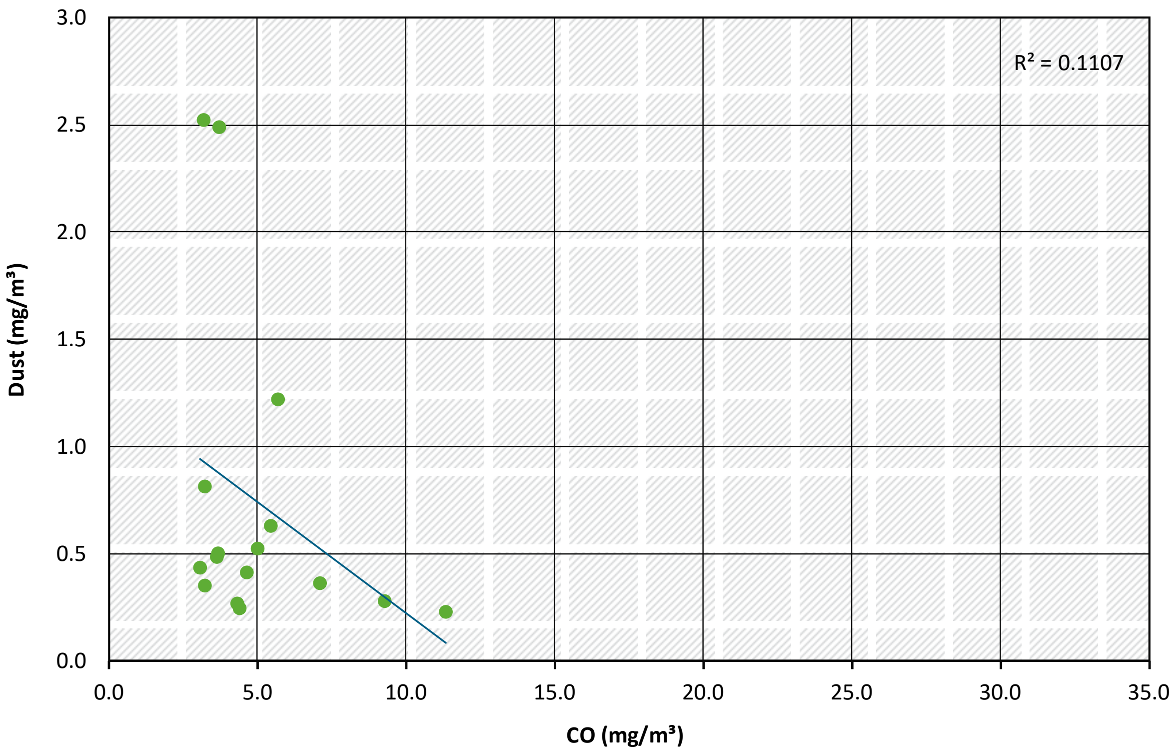
Figure 57: Correlation dust and carbon monoxide - natural gas plants



Source: own figure (Ökopol)

As the measured values contain two particularly high values, the correlation was also analysed without these two values. Based on the remaining 16 pairs of measured values, the correlation coefficient is -0.33, which indicates a low correlation. (Figure 58)

Figure 58: Correlation dust and carbon monoxide - natural gas plants (without two highest values)



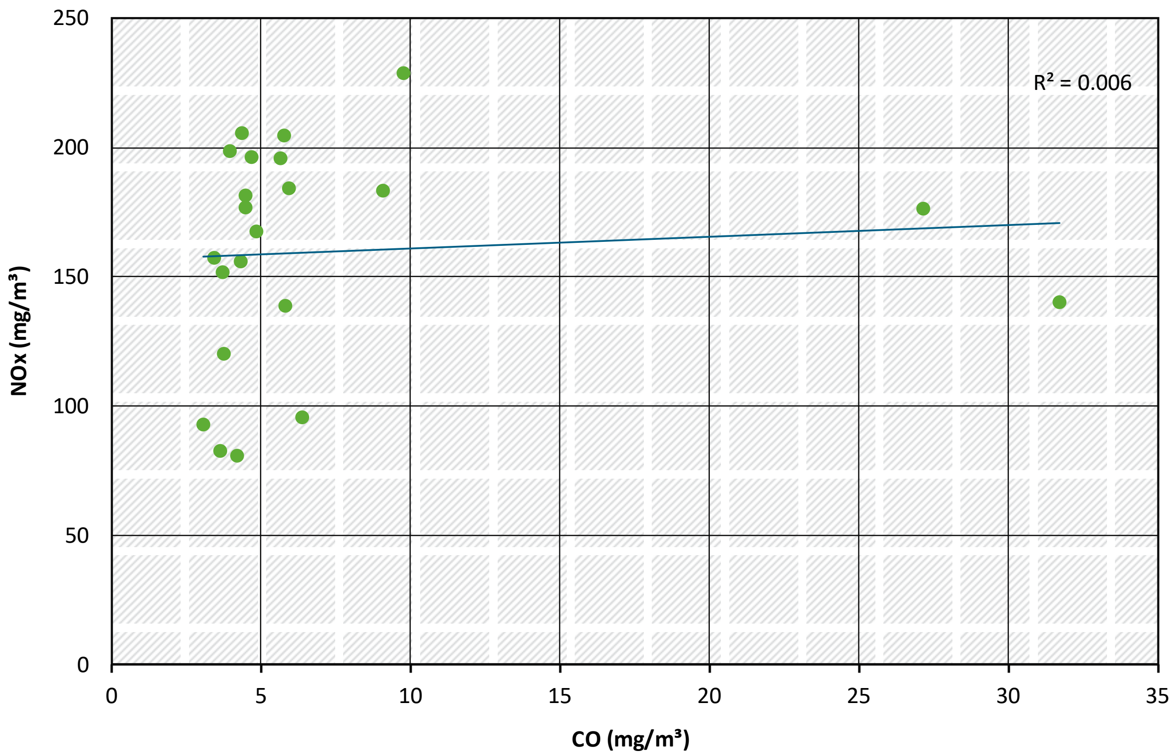
Source: own figure (Ökopol)

3.6.8 Nitrogen oxides and carbon monoxide

At high temperatures in the range of 850 °C and NO_x concentrations of several hundred milligrams per cubic metre, it can be observed that a reduction in temperature is accompanied by an increase in the carbon monoxide concentration and a reduction in the concentration of nitrogen oxides and vice versa with an increase in temperature. It was therefore examined whether there is also a correlation between emissions of nitrogen oxides and carbon monoxide in medium combustion plants with 1 to less than 10 MW.

The analysis of the correlation between nitrogen oxides and carbon monoxide in fuel oil combustion is based on 22 pairs of measured values above the limit of quantification and results in a correlation coefficient of 0.077. Therefore, no correlation can be observed. (Figure 59)

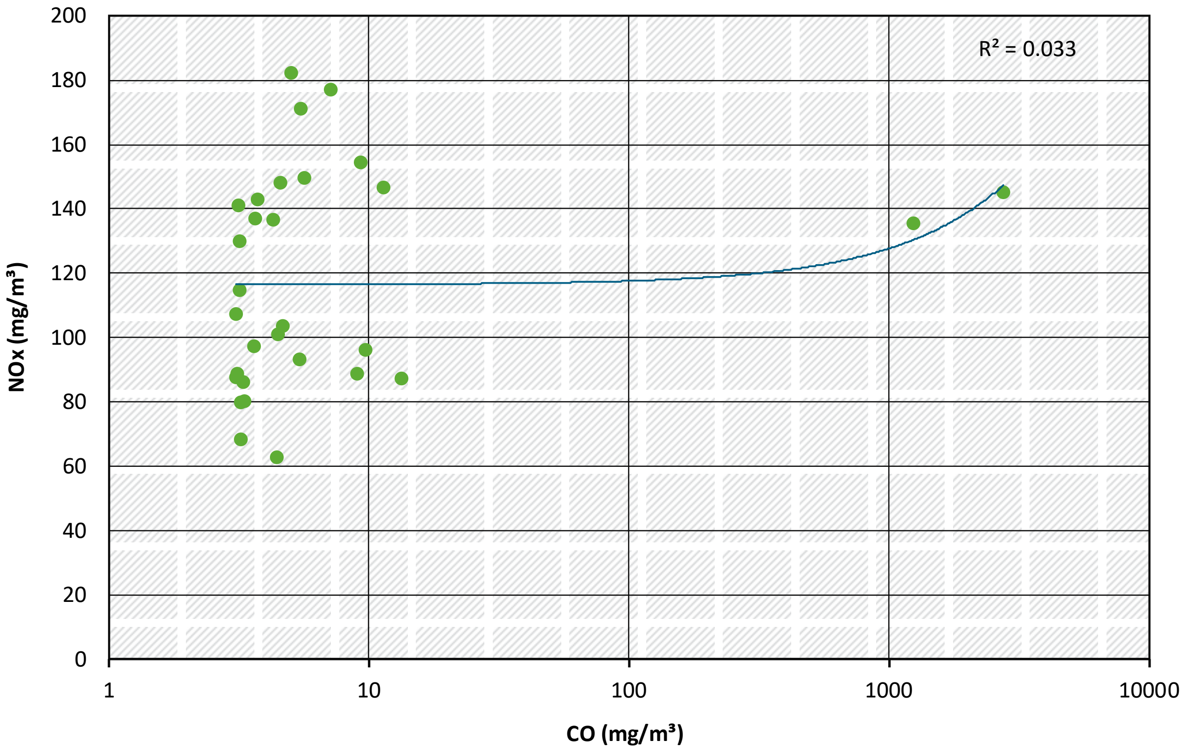
Figure 59: Correlation of nitrogen oxides and carbon monoxide - fuel oil plants



Source: own figure (Ökopol)

The correlation coefficient between nitrogen oxides and carbon monoxide in natural gas combustion is based on 30 pairs of measured values above the limit of quantification and is 0.18. As the value is close to zero, there is also no correlation. (Figure 60)

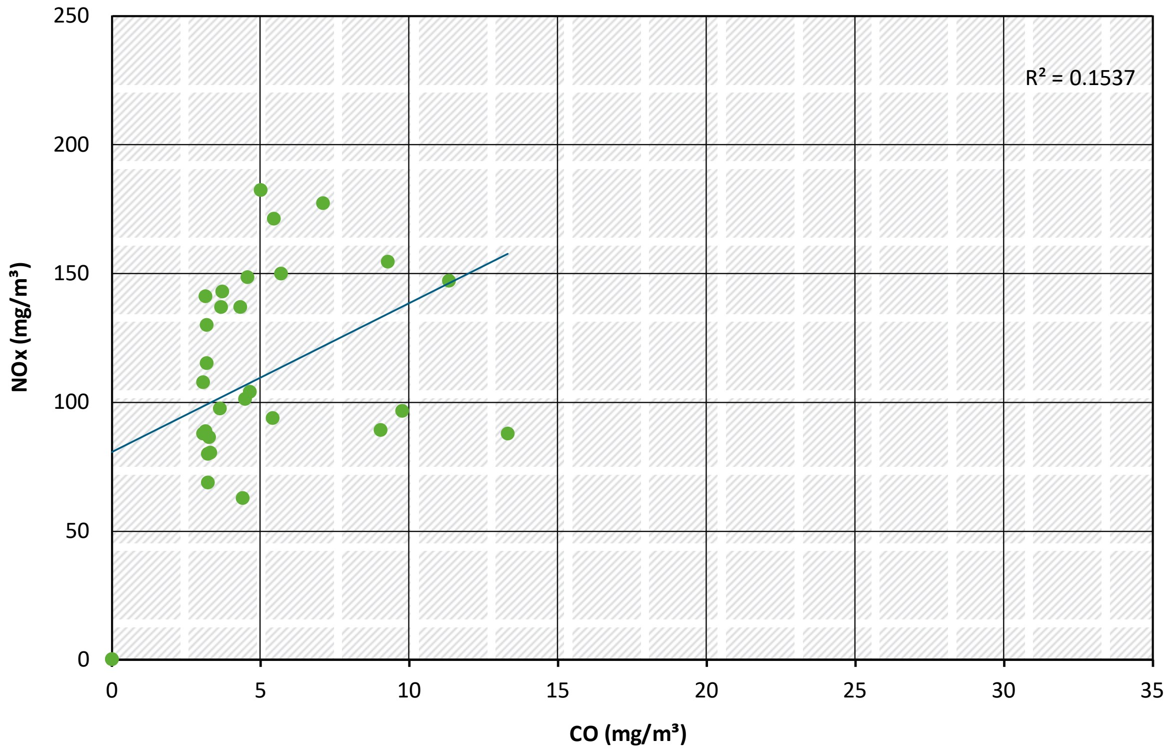
Figure 60: Correlation of nitrogen oxides and carbon monoxide - natural gas plants



Source: own figure (Ökopol)

If the two highest values are excluded, the correlation coefficient of nitrogen oxides to carbon monoxide for natural gas combustion remains very small at 0.14. (Figure 61)

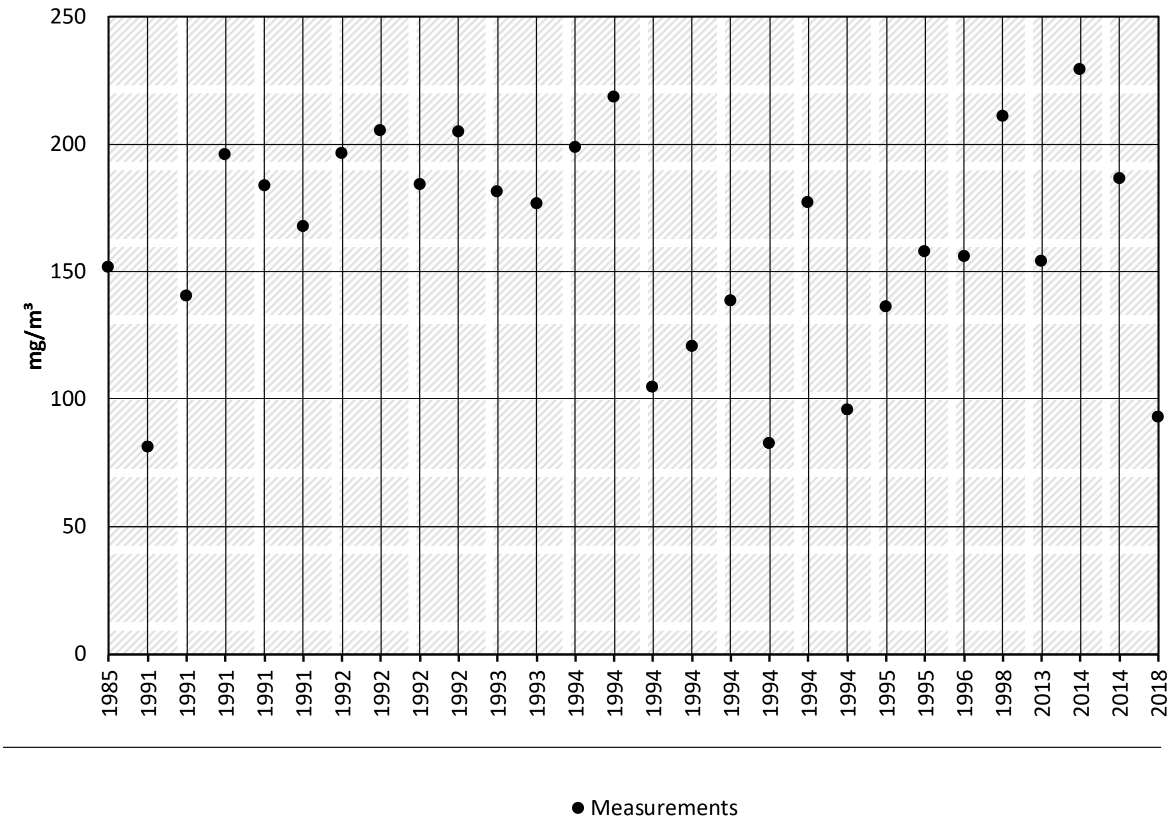
Figure 61: Correlation of nitrogen oxides and carbon monoxide - natural gas plants (without two highest values)



Source: own figure (Ökopol)

A correlation of NOx values with the year of plant commissioning does not exist, neither for fuel oil plants (Figure 62) nor for existing natural gas plants. The five new natural gas plants (commissioned from 20.12.2018) show lower NO_x values. (Figure 63)

Figure 62: Correlation of nitrogen oxides and year of commissioning – fuel oil plants (standardised, 3 % oxygen content, mean value of three measurements of usually 30 minutes)



Source: own figure (Ökopol)

Figure 63: Correlation of nitrogen oxides measurement values and year of commissioning – natural gas plants (standardised, 3 % oxygen content, mean value of three measurements of usually 30 minutes)

Source: own figure (Ökopol)

4 Best available techniques for emission reduction for oil and gas combustion plants with 1 - < 10 MW

This chapter documents the results of research into the possibilities for reducing emissions from medium oil and gas combustion plants with a rated thermal input of 1 MW to less than 10 MW and, in particular, includes the information obtained at a workshop with manufacturers, associations and authorities on the same topic.

4.1 Overview

Table 56 lists emission reduction techniques that can generally be applied to medium oil and gas combustion plants with a rated thermal input of 1 MW to less than 10 MW, as well as the pollutants reduced. A large cross in bold indicates the main effect of the technique, a small cross the secondary effects for further pollutant reductions. An increase in energy efficiency is also listed as an emission reduction technique because it leads to specifically lower emissions per unit of heat emitted.

The 100 measurements on medium oil and gas combustion plants with a nominal heat output of 1 MW to less than 10 MW have shown that the plants have relatively low emissions of dust, carbon monoxide, methane and other organic carbon compounds. Sulphur dioxide emissions were not measured, as they are generally emitted in proportion to the sulphur in the fuel used and can be reduced with appropriate low-sulphur fuels (natural gas or low-sulphur fuel oil).

Relevant emissions from the plants are primarily caused by the formation of nitrogen oxides from air nitrogen and from fuel nitrogen. The use of low-sulphur fuel oil contributes to the reduction of NO_x formation from fuel nitrogen, as its production also reduces the nitrogen content. When using natural gas as a fuel, there is no possibility of selecting low-nitrogen gas types due to the fixed connection. In addition to the use of low-nitrogen fuels, various techniques are available to reduce the formation of NO_x. The possibilities for NO_x reduction of the various boiler designs specified by burner manufacturers are shown in Table 87 in the appendix J.

Table 56: Emission reduction techniques for oil and gas-fired combustion plants with 1 - < 10 MW

Pollutant technique	NO_x	SO_2	CO	TOC	NMVOC	Dust	Energy efficiency
Waste gas heat utilisation	x	-	x	x	x	x	**X**
Lambda sensor/O_2 control	x	-	x	x	x	x	**X**
Low-sulphur fuels	x	**X**	-	-	-	-	-
Exhaust gas recirculation (external)	**X**	-	x	x	x	x	x
Exhaust gas recirculation (internal)	**X**	-	x	x	x	x	x
Low NO_x burner	**X**	-	-	-	-	-	-
Non-catalytic reduction (SNCR)	**X**	-	-	-	-	-	-
Catalytic reduction (SCR)	**X**	-	-	-	-	-	-

Source: Own research (Ökopol)

4.2 Flue gas heat utilisation

4.2.1 Description of the technique

In flue gas heat utilisation, the energy remaining in the flue gas is transferred to another medium through heat exchangers, thus making better use of the fuel used.

Possible uses are:

- Combustion air preheating
- Boiler water, thermal oil, drying air heating
- Water heating for purposes other than boiler water

When the flue gases are cooled to below 100°C, water vapour condensation occurs (calorific value utilisation). The acidic condensate must be filtered and neutralised before it can be discharged into the sewage system. This protects waste water pipes from corrosion and retains solid flue gas components.

Typical flue gas heat exchanger applications for heating support increase the water temperature by 10-20 K. This reduces the flue gas temperature from approx. 175 °C to approx. 65 °C. (Bomat Überlingen 2022)

4.2.2 Achieved environmental benefits

- Reduction of all pollutant emissions in relation to the fuel energy used
- Reduction in fuel consumption due to lower energy consumption

The increased energy yield through flue gas heat utilisation leads to lower specific emissions of all pollutants per energy used, as the energy supplied to the heat exchanger system does not have to be provided by additional fuels and thus emissions otherwise caused by other energy sources are eliminated.

The technique leads to lower consumption of raw materials because the energy sources otherwise required for the heat exchanger system are no longer needed. When supporting a heating system, the flue gas heat exchanger can increase efficiency by up to 10 %, depending on the operating status of the plant. (Bomat 2022)

The reduction in pollutants cannot be quantified across the board. It depends on the temperature level of the exhaust gases, the usability of the waste heat in the respective energy system and the emissions of the generation system that is replaced by the waste heat utilisation.

4.2.3 Applicability

In principle, there are no restrictions to applicability for the technique. However, spatial restrictions are possible when retrofitting, as there is not always the possibility of retrofitting between the boiler flue gas outlet and the chimney. The heat exchanger must have DIBt type approval and the existing chimney system must also be approvable for the heat exchanger, otherwise the chimney must be replaced in addition to the heat exchanger. When using fuel oil containing sulphur, sulphuric acid corrosion must be expected in the chimney when the flue gas cools down.

- Combustion air preheating: generally applicable, but increased NOx formation

There are no technical restrictions on utilising the heat contained in the exhaust gas to preheat the combustion air. However, preheating the combustion air leads to an increased flame temperature and thus to increased NO_x emissions, so that this effect may be the limiting factor for combustion air preheating when emissions are close to the NO_x limit value. x

- Boiler water, thermal oil, drying air preheating: generally applicable if there is a sufficient temperature difference between the flue gas and the heat exchanger medium

In principle, there are few restrictions on the use of preheating. However, the temperature difference between the exhaust gas and the heat exchanger medium must be sufficiently large for the installation to be economical. If the waste heat temperature is not sufficiently above the return temperature of the boiler water, thermal oil or circulating air of a drying system, economic utilisation is not possible. If a drying system is operated without circulating air, economic utilisation of the waste heat is generally possible.

- Utilisation for purposes other than boiler water/thermal oil/drying air: generally applicable

The main application restriction is the frequent lack of utilisation possibilities if the options described above are not applicable. If the boiler is operated intermittently, this is not a limitation for waste heat utilisation, as the waste heat can be made available via a buffer storage tank.

4.2.4 Cross-media effects

- Resource consumption

A flue gas heat exchanger is associated with a low additional consumption of resources for the provision of the required equipment (heat exchanger, neutralisation system, fan). If necessary, a flue gas heat exchanger leads to further consumption of resources for the construction of a new chimney and possibly a buffer storage tank.

Low operating resources are required for the neutralisation system.

- Energy consumption

As the flue gas temperature downstream of the heat exchanger is generally too low to transport the flue gas out of the chimney at a sufficient speed, a fan must be operated. Just like the operation of the pump in the neutralisation system, this leads to additional (electricity) consumption.

- Wastewater generation

In flue gas heat exchangers, when the flue gas is cooled below 100°C, condensation water is formed, which increases the salt load in the waste water. When used for boiler water preheating, this amounts to around 1.5 litres per cubic metre of natural gas and 0.9 litres per litre of fuel oil. (Rosenkranz 2020)

- Increased air emissions

If the combustion air temperature is preheated, there is no cooling of the flame in the hottest zone of the burner, which causes an increase in nitrogen oxides emissions.

4.2.5 Costs

The costs depend on the size of the system and the effort required to connect the pipework for the heat exchanger medium. If the boiler water of a heating system is to be preheated, the costs for a 1 MW plant amount to a few thousand euros.

In addition to the installation costs, the amortisation period depends largely on the energy costs. In recent years, it has usually been less than 5 years (Bomat 2022). It is to be expected that the amortisation period will fall in future as energy costs rise disproportionately to installation costs.

4.3 Lambda sensor/oxygen control

4.3.1 Description of the technique

A lambda sensor or oxygen control system utilises the measurement of the oxygen content in the combustion chamber or exhaust gas flow. The measurement signal is used to optimise the combustion air supply to the optimum oxygen/fuel ratio (lambda = λ).

Plants with a rated thermal input of 1 MW to less than 10 MW can usually vary the output ("modulate"). When modulating, measuring the oxygen content ensures a more precise combustion air dosage than a setting analogue to the fuel supply.

This optimises combustion, i.e. the fuel is better utilised and fewer emissions are produced than if combustion were under- or over-stoichiometric. In the case of under-stoichiometric combustion, there is a lack of oxygen, resulting in the formation of carbon monoxide and organic carbon compounds; in addition, fuel components are released into the exhaust gas (e.g. methane). In the case of over-stoichiometric combustion, the combustion chamber becomes hotter, and more nitrogen is fed into the flame, which contributes to an increase in NO_x emissions. In addition, more heat escapes with the flue gas as it cannot be used in the boiler.

Lambda sensors optimise combustion not only by modulating the burner output, but also when the fuel composition fluctuates. Fluctuating fuel calorific values will become more important in the future, especially in natural gas combustion, because LNG supplies will increasingly mix qualities from different producers into the natural gas network and increased quantities of hydrogen produced from renewable energy sources will also be added. (Avacon 2022)

4.3.2 Achieved environmental benefits

- Reduction of all pollutant emissions
- Reduction in the use of raw materials due to lower energy consumption

Optimised combustion using lambda sensors leads to lower specific emissions of all pollutants per energy input, because under-stoichiometric ratios (which lead to unburned fuel components in the exhaust gas) are prevented, as are over-stoichiometric ratios (which increase NOx emissions and cause greater heat loss via the exhaust gas).

The technique leads to lower consumption of raw materials because the fuel is used more efficiently.

4.3.3 Applicability

- Lambda sensors are generally applicable, also as a retrofit for existing plants.

4.3.4 Cross-media effects

- Resource consumption

Lambda sensors are associated with low additional resource consumption for the provision of measurement and control technique (measuring probe, software).

- Energy consumption

Lambda sensors are associated with low additional (power) consumption.

4.3.5 Costs

A lambda sensor for a burner costs around EUR 3,000 (UBA workshop 2022).

4.4 Low-sulphur and low-nitrogen fuels

4.4.1 Description of the technique

The emission of sulphur dioxide in combustion plants with 1 to less than 10 MW is proportional to the use of sulphur in the fuel, as no SO_2 reduction technique is used. The use of low-sulphur fuels therefore leads to reduced sulphur dioxide emissions.

In the case of fuel oil, the "EL fuel oil" grade may only be placed on the market with a maximum sulphur content of 1.0 g/kg (10th BImSchV 2019). The "EL low-sulphur fuel oil" grade, which dominates in Germany due to lower taxes, may contain a maximum of 50 mg/kg S content in accordance with the relevant DIN standard (DIN 51603-1:2020). This means that the maximum net-calorific value-related sulphur content of "EL low-sulphur fuel oil" is around 4.2 mg/kWh and the sulphur content of "EL fuel oil" is around 84 mg/kWh.

In addition to a lower sulphur content, the "EL low-sulphur fuel oil" grade also has a lower nitrogen content due to the production process, which is usually less than 140 mg/kg. Since September 2020, the standard for fuel oils has designated a separate grade "EL fuel oil low sulphur, low nitrogen", which may contain a maximum of 140 mg/kg nitrogen (DIN 51603-1:2020). However, this grade has not yet been offered by retailers (see HeizOel24 2022, Nordoel 2022). A maximum content of 140 mg/kg is not guaranteed in the "EL low-sulphur fuel oil" grade (Experts exchange 2022), but dealer information indicates that experience has shown that low-sulphur products always contain less than 140 mg/kg nitrogen (cf. Nordoel 2022).

A retailer in Switzerland informs that a maximum nitrogen content of 100 mg/kg of fuel was guaranteed for the low-sulphur Swiss grade "eco fuel oil", which results from the desulphurisation of the fuel oil. According to the retailer, the EL fuel oil in standard quality has an average nitrogen content of 150 mg/kg. (Oel Schenk 2022)

4.4.2 Achieved environmental benefits

- Reduction of pollutant emissions of sulphur dioxides and nitrogen oxides

4.4.3 Applicability

- EL low-sulphur fuel oil can generally be used
- EL low-sulphur, low-nitrogen fuel oil can also generally be used

4.4.4 Cross-media effects

- Resource consumption
- Energy consumption

The production of "EL low-sulphur fuel oil" is associated with higher (crude oil) energy consumption for desulphurisation ("hydrofinishing") compared to EL fuel oil. The process consumes mineral resources (e.g. nickel, molybdenum, cobalt) for catalysers. The sulphur subsequently extracted in "Claus" plants replaces natural sulphur as a raw material.

4.4.5 Costs

The "EL low-sulphur fuel oil" grade dominates the market.

4.5 Exhaust gas recirculation

4.5.1 Description of the technique

With flue gas recirculation, part of the flue gas is fed back to the burner as combustion air. Exhaust gas recirculation can take place outside the combustion chamber ("external recirculation"), inside the combustion chamber or in the burner ("internal recirculation").

The oxygen from the supplied combustion air is already largely oxidised in the recirculated exhaust gas flow, so that nitrogen oxides can no longer be produced from this air component. Unburnt exhaust gas components (carbon monoxide and organic carbon compounds, including any soot particles formed) can be burnt out more effectively when returned to the flame.

4.5.2 Achieved environmental benefits

- Reduction of all pollutant emissions, especially NO_x reduction

Flue gas recirculation leads to lower specific emissions of all pollutants per energy input because the burnout of unburnt carbon compounds is improved and nitrogen oxides emissions are reduced. However, care must be taken to ensure that the flue gas is not recirculated from a zone that is too hot, as otherwise the nitrogen oxides emissions will increase due to the higher flame temperature.

4.5.3 Applicability

- External exhaust gas recirculation: generally applicable; retrofitting may be subject to spatial restrictions.

When retrofitting the technique, space restrictions are possible, as there is not always the option of retrofitting at the boiler flue gas outlet and at the burner.

- Internal flue gas recirculation: generally applicable; retrofitting is only possible by replacing the burner or the boiler.

4.5.4 Cross-media effects

- Resource consumption

Exhaust gas recirculation is associated with low additional resource consumption for the installation of the required pipework and fans.

- Energy consumption

In addition, the recirculation of exhaust gases by fans results in additional (electricity) energy consumption, which may be associated with emissions depending on the source.

4.5.5 Costs

The costs of external flue gas recirculation depend on the cost of installing the pipework and modifying the burner control system. They generally amount to a few thousand euros (Workshop 2022).

The costs of internal flue gas recirculation cannot be quantified, as flue gas recirculation is offered as an integrated component of a boiler or burner (and not separately).

4.6 Low NOx burner

4.6.1 Description of the technique

Lowering the temperature in the "flame root" and exhaust gas recirculation: A defined fuel distribution from the centre to the outside prevents the temperature at the flame root from rising to over 1300°C. Exhaust gas recirculation increases the speed of the combustion gases. Nitrogen and oxygen can leave the hot reaction zone more quickly. In addition, the fuel can be divided up in the burner by design measures so that a primary and a secondary flame are created. The primary flame ensures flame stability and the development of the secondary flame.

4.6.2 Achieved environmental benefits

In 2012, the Flemish research institute VITO published a BAT study on new small and medium combustion plants, stationary engines and gas turbines fuelled with fossil fuels (Dils/Huybrechts 2012). No measurement data from new plants was available for the study. The estimation of the emission values achievable with reduction techniques is mainly based on information from manufacturers and the emission values they guarantee. In 2012, the authors concluded that an emission limit value for nitrogen oxides of 185 mg/Nm³ for (then) new fuel oil-fired plants with 1 - < 5 MW could be achieved with best available techniques (BAT), in this case low NO_x burners, without deducting or adding measurement uncertainty. In the "low-cost scenario", the use of SCR as BAT is also envisaged, whereby a limit value of 40 mg/Nm³ is associated with BAT.

For existing plants, information can be found in a BAT study on combustion plants and stationary engines carried out by VITO in 2002 (Govaerts et al. 2002).

According to the Federal Association of the German Heating Industry (BDH), in which the burner manufacturers are represented, compliance with a limit value for nitrogen oxides with natural gas of 40 - 80 mg/Nm³ and with fuel oil of 100 - 150 mg/Nm³ (without addition or deduction of the measurement uncertainty) can be guaranteed for large-capacity boilers based on the through-firing principle with low NO_x burners and a combination of internal and external flue gas recirculation (see in the appendix. Table 87). (UBA workshop 2022)

Influencing factors are:

- Boiler temperature (depending on the utilisation, e.g. for warm/hot water, steam, thermal oil, drying air)
- Nitrogen content of the fuel (see chapter 4.4)
- Stability of the flame
- Moisture content of the combustion air during measurement (influenced by the weather)

4.6.3 Applicability

- Low NOx burners can generally be used except for reverse flame boilers.

Difficulties can arise because the low NOx burner generally has a lower output than the standard burner installed in the same boiler due to the reduced flame temperature. If the drop in output leads to an undersupply of the connected heat users, the burner may not be fit for purpose.

4.6.4 Cross-media effects

The industry assumes efficiency losses (see Appendix J, page 210). However, the EU BREF for large combustion plants states that no efficiency losses are measured. Higher CO emissions may occur at low load due to the cooler, longer flame. (EU BREF LCP 2017, page 203)

4.6.5 Costs

No information.

4.7 Selective non-catalytic reduction (SNCR)

4.7.1 Description of the technique

The technique uses urea or ammonia water, which is injected into the exhaust gas. In the ideal temperature zone, which is between 900 and 1050°C, the injected reagent reacts with the nitrogen oxides present in the exhaust gas to form inert nitrogen (N_2).

4.7.2 Achieved environmental benefits

- Reduction of nitrogen oxides emissions

With selective non-catalytic reduction (SNCR), around 40 - 50 % nitrogen oxides reduction can be achieved in medium combustion plants (UBA workshop 2022).

4.7.3 Applicability

- SNCR can only be used if the temperature window required for the reaction is available and if the reagent has a sufficient reaction time.

The appropriate temperature window must also be available when the load fluctuates so that emissions are continuously reduced by the SNCR.

4.7.4 Cross-media effects

- Emissions into the air: ammonia (NH_3)

When the technique is used, the over-stoichiometric injection of urea or ammonia water leads to an increase in ammonia emissions ("NH_3 slip"). Emissions can be minimised by continuously measuring the temperature in the injection area. The measurement is carried out using infrared technique, for example, which is installed in the injection area. This allows the stoichiometry during injection to be optimised to achieve maximum ammonia emission reduction with SNCR.

- Raw material consumption

The use of an SNCR involves a relatively small amount of technical equipment (storage tanks, pipes, pumps, valves, software for dosing), which leads to a consumption of raw materials. Added to this is the consumption of ammonia or urea.

- Energy consumption

The use of an SNCR is associated with additional (electricity) energy consumption, which can lead to emissions depending on its source. The use of urea or ammonia water is associated with considerable raw material and energy consumption in mining and in the production of the reagent. The production of ammonia is estimated to consume around 30 GJ/t of energy (EU BREF LVIC-AAF). Ammonia production leads to emissions into water and air.

4.7.5 Costs

The installation of a SNCR system is associated with costs of around EUR 50,000 for medium combustion plants with 1 MW to less than 10 MW, regardless of the capacity of the plant (UBA workshop 2022)

4.8 Selective catalytic reduction (SCR)

4.8.1 Description of the technique

The technique uses a catalytic converter that selectively reduces nitrogen oxides in the exhaust gas to inert nitrogen (N_2). The reaction is intensified by the addition of urea or ammonia water, which is injected into the exhaust gas. The catalytic converter requires an exhaust gas temperature of at least around 350 °C for the reaction.

The catalytic converters have a long service life, which is generally 16-20,000 hours for fuel oil and 32-36,000 hours for natural gas. (ERC 2022)

4.8.2 Achieved environmental benefits

- Reduction of nitrogen oxides emissions

With SCR, nitrogen oxides reduction rates of a maximum of around 90 % can be achieved in medium combustion plants (UBA workshop 2022).

In 2011, the Flemish research institute VITO carried out a BAT study on new small and medium combustion plants, stationary engines and gas turbines fuelled with fossil fuels. As already mentioned, no measurement data from new plants was available for the study. An estimate of the emission values achievable with reduction techniques was made, based mainly on information from manufacturers and the emission values guaranteed by them. In 2012, the authors concluded that in the "low-cost scenario" for (then) new fuel oil-fired plants with 1 MW - < 5 MW, an emission value for nitrogen oxides of 40 mg/Nm^3 with SCR is achievable with best available techniques (BAT). (Dils/Huybrechts 2012)

According to one manufacturer, under ideal conditions, 30 mg/Nm^3 can be achieved when retrofitting medium combustion plants for natural gas combustion (UBA workshop 2022).

4.8.3 Applicability

Space restrictions may hinder retrofitting the technique, as it is not always possible to retrofit the boiler flue gas outlet.

4.8.4 Cross-media effects

- Raw material consumption
- Energy consumption

The construction of the SCR involves a relatively high level of technical equipment (catalytic converter and housing, fans, supply lines, reagent tank), which is associated with a relatively high consumption of raw materials (e.g. for stainless steel, vanadium). The operation of the plant is associated with (electrical) energy consumption for the operation of fans and compressed air equipment.

The production and utilisation of the reagent (urea or ammonia water) is associated with raw material and energy consumption (see previous chapter).

4.8.5 Costs

In contrast to SNCR, the technical equipment required for SCR is more complex, but the operating costs are significantly lower due to the lower ammonia and urea consumption. For medium combustion plants in the capacity range under consideration, the investment costs for reduction rates of 90 % are given as around EUR 100,000 (UBA workshop 2022). These costs are also quoted by a calculation programme for NO_x reduction in MCPD plants developed by the Netherlands (IPLO 2022).

5 Comparison of the requirements for fuel oil and natural gas combustion plants with 1 - < 10 MW in selected European countries

This chapter documents the research on requirements for oil and gas combustion plants with a rated thermal input of 1 MW to less than 10 MW in Denmark, Germany, Flanders (Belgium), the Netherlands, Austria and Switzerland. The information was gathered through literature research, contacts with people responsible for regulating medium combustion plants and a workshop on the topic (UBA workshop 2022).

5.1 Overview of selected European countries

Table 57 provides an overview of limit values and measurement requirements for medium combustion plants in six selected European countries. The requirements in the countries analysed differ significantly from one another.

Firstly, the parameters measured are slightly different in the countries analysed. The Netherlands, for example, only requires compliance with a limit value for nitrogen oxides for natural gas combustion plants, while the other five countries also set limit values for carbon monoxide. Flanders also requires natural gas combustion plants to comply with limit values for sulphur dioxide and dust. When using liquid fuels, all the countries analysed set limit values for nitrogen oxides and - with the exception of Denmark and the Netherlands - for dust, carbon monoxide or the smoke number. In addition to CO, NOx, dust or the smoke number, Flanders also requires compliance with limit values for two heavy metals (vanadium and nickel) for liquid fuel combustion plants.

An examination of the limit values shows that in most cases lower limit values have been set by countries that deduct the measurement uncertainty from the measurement result. However, this is not the case for all parameters. For example, the CO limit value for new plants is similar in Austria and Germany, although the measurement uncertainty in Austria must be subtracted and in Germany it must be added. The NO_x limit values for natural gas combustion plants in Flanders and the Netherlands do not differ significantly, although the measurement uncertainty is added in Flanders and subtracted in the Netherlands.

The measurement periods for smaller plants with 1 MW to less than 5 MW are two years in Belgium, Denmark and Switzerland compared to three years in Austria, Germany and the Netherlands. For plants with 5 MW or more, the measurement periods in Flanders and Denmark are significantly shorter (three months and one year respectively) than in the other four countries, where they are two years (Switzerland) or three years (Austria, Germany, Netherlands).

The required measurement duration is mostly three times 30 minutes, except in Flanders, where it is once 60 to 90 minutes, and Denmark, where twice 45 minutes duration is required.

The limit value is sometimes compared with the average value of the individual measurements (Denmark, Switzerland), sometimes each individual value is used for comparison with the limit value (Germany, Netherlands).

Table 57: Requirements for existing medium combustion plants in Flanders/Belgium, Denmark, Switzerland, Austria, Germany and the Netherlands

	Flanders/BE (1-20 MW)	DK (< 10 MW)	CH (< 10 MW)	AT (1-20 MW)	DE (1-10 MW)	NL (1-20 MW)
Limit values Natural gas (range min.-max.)[7] [mg/Nm3]	NOx: 80-300 CO: 100-250 SO_2: 35 Dust: 5-50	NOx: 100-105 CO: 125	NOx: 80 CO: 100 NH_3: 30	NOx: 100-120 CO: 80	NOx: 100-150 CO: 80-110	NOx: 70
Fuel oil limit values (range min.-max. 0)[8] [mg/Nm^3]	NOx: 185-650 CO: 175-250 SO_2: 170-1700 Dust: 5-200 Nickel: 3 Vanadium: 5	NOx: 180 CO: 165	NOx: 80 CO: 100 NH_3: 30 Smoke number: 1	NOx: 150 CO: 80 Dust: 10-20	NOx: 200 CO: 80-150 Smoke number: 1	NOx: 120 SO_2: 200 Dust: 5
Requirement regarding measurement uncertainty	Addition	No conside-ration	Subtraction	Subtraction	Addition	Subtraction
Measurement uncertainty max.	All parameters: 30 %	-	-	NOx: 20 % CO: 10 % Dust: 30 %	-	NOx: 20 % SO_2: 20 % Dust: 30 %
Measurement duration	One measurement (60 min. or 90 min.)	2 x 45 minutes	3 x 30 minutes	3 x 30 minutes	3 x 30 minutes	3 x 30 minutes
Limit value adjustment	Average of all individual values	Average of all individual values	Average of all individual values	Each individual value	Each individual value	Each individual value
Load status during the measurement	Typical load condition	-	Multiple load statuses	Typical load condition	Typical load condition	At least 60 % load
Measuring periods (only plants > 500 annual operating hours)	Every 2 years for 1 - < 5 MW Every 3 months for 5 - < 20 MW	Every 2 years for < 5 MW Once per year for	Every 2 years	Every 3 years	Every 3 years	Every 3 years for new plants Once for existing plants

[7] The emission limit values (given in ranges) depend on the system capacity, the operating hours and the date of the first licence (existing/new).

[8] The emission limit values (given in ranges) depend on the system capacity, the operating hours and the date of the first licence (existing/new).

	Flanders/BE (1-20 MW)	DK (< 10 MW)	CH (< 10 MW)	AT (1-20 MW)	DE (1-10 MW)	NL (1-20 MW)
		5 - < 10 MW and > 3000 hours/a				(every 3 years from 2025 for ≥ 5 MW and from 2030 for 1 - 5 MW)
Techniques and BAT	Low NOx burners are standard for existing and new plants	n. s.	Large proportion of dual-fuel burners and trend towards switching to fuel oil; ban on heavy fuel oil	Low NOx burners are standard for existing and new plants	Low NOx burners are the standard for new plants	Low NOx burners are the standard for existing and new plants

Source: UBA workshop (2022)

5.2 Denmark

The EU Directive for medium combustion plants (EU Directive 2015) is transposed into national law in Denmark by Decree No. 1535 (BEK 2019). The requirements were integrated into an existing regulation from 2001.

5.2.1 Limit values

Table 58 shows the emission limit values of the decree for combustion plants up to less than 10 MW.

Table 58: Emission limit values for combustion plants < 10 MW (3 % O_2) in Denmark

Fuel	Plant age	NO_x [mg/Nm³]	SO_2 [mg/Nm³]	CO [mg/Nm³]
Natural gas	Existing plants	105*	-	125
	New plants	100	-	125
Biogas	Existing plants	105**	200**	125
	New plants	105	100	125
Fuel oil	Existing plants	180	-	165
	New plants	180	-	165

* 200 mg/Nm³ for plants authorised before June 2001

** 170 mg/Nm³ for plants > 5 MW

Source: BEK (2019)

5.2.2 Measurements

The measurement periods in Denmark depend on the plant capacity and the operating hours. Unlike in the other countries analysed, two individual measurements of 45 minutes each are required (instead of three times 30 minutes in most of the countries analysed). The limit value is complied with if the arithmetic mean, calculated from the results of the individual measurements, is less than or equal to the limit value.

Table 59 shows the measurement periods for checking compliance with the emission limit values for medium combustion plants (< 10 MW).

Table 59: Measurement periods for medium combustion plants (< 10 MW) in Denmark

Nominal heat output or operating hours	≤ 5MW	Natural gas and fuel oil: > 5 - < 10 MW and ≤ 3000 operating hours per year[9]	Natural gas and fuel oil: > 5 - < 10 MW and > 3000 operating hours per year[10]	Biogas: < 10 MW
Measuring period	Every 2 years	Every 2 years	Annually	Annually

Source: BEK (2019)

[9] As a moving average over a period of five years

[10] As a moving average over a period of five years

5.2.3 Measurement uncertainty

In Denmark, the measurement uncertainty is not taken into account when checking the limit value.

5.2.4 Techniques used and measured values

Information on the reduction techniques used and current measured values is not available at the responsible environmental agency (UBA workshop 2022).

5.3 Germany

In Germany, the 44th BImSchV transposes the EU Directive (2015) into national law.

Low NOx burners and O_2 control are rarely used in existing plants. The installation of low NOx burners in new plants is common. SCR and SNCR techniques are not used in fuel oil and natural gas combustion plants with 1 - 10 MW. (UBA workshop 2022)

5.3.1 Limit values

The 44th BImSchV includes limit values for the parameters NOx, CO and smoke number. A maximum waste gas heat loss is also to be complied with. Table 60 lists the emission limit values for plants with a rated thermal heat output of 1 MW to less than 10 MW.

Table 60: Emission limit values for combustion plants 1 - < 10 MW (3 % O_2) in Germany

Fuel	Plant type	NOx [mg/Nm³]	CO [mg/Nm³]	Smoke number	Exhaust gas heat loss
Natural gas	New plants	100	80	-	9 %
	Existing plants	- (150)*	110	-	9 %
Fuel oil	New plants	200	80	1	9 %
	Existing plants	- (200)*	150	1	9 %

* From 1 January 2025, until then the plants must demonstrate compliance with NO_x values on the test bench, which are 185 mg/kWh for fuel oil and 120 mg/kWh for natural gas combustion plants with a nominal heat output of more than 400 kW (1st BImSchV 2010).
Source: 44th BImSchV (2019)

5.3.2 Measurements

Table 61 lists the measurement cycles specified in the 44th BImSchV. Measurements must be carried out every three years for both existing and new plants with a rated thermal input of 1 MW to less than 10 MW. Each measurement cycle comprises three half-hour measurements. The plant must "run under stable conditions at a representative even load" (44th BImSchV 2019). Where possible, it is common practice to carry out at least one of the individual measurements during full load (UBA workshop 2022).

The measurement must be carried out by authorised measuring institutes. Plants with 1 MW to less than 10 MW that do not require a permit may also be measured by chimney sweeps.

Table 61: Measurement periods for medium combustion plants (1 - < 10 MW) in Germany

Plant type	1 - < 10 MW
Existing plants	Every 3 years
New plants	Every 3 years

Source: 44th BImSchV (2019)

5.3.3 Measurement uncertainty

The limit values are complied with if no result of an individual measurement plus the measurement uncertainty exceeds an emission limit value.

The amount of the added measurement uncertainty depends on the measuring devices and conditions. The authorised measuring bodies determine the uncertainty of the measuring methods used. The chimney sweeps use measuring devices with a device-specific measurement uncertainty, which is specified for oil and gas combustion plants in VDI Guideline 4206-1 (2010).

5.3.4 Techniques used and measured values

For information on the emission reduction techniques used, see chapter 3.2. For current emission values, see chapters 3.4 and 3.5.

5.4 Flanders (Belgium)

In Belgium, environmental policy is regulated at regional level, with slightly different legislation and limit values applying to the three regions of Flanders, Wallonia and Brussels. The Flanders region was analysed in the project.

In Flanders, the EU Directive on medium combustion plants (EU Directive 2015) is transposed into regional law by the Flemish government decree "VLAREM II" (2022).

The EU requirements were integrated into an existing regulation. By differentiating the limit values according to various age groups, the regulations are significantly more extensive compared to the other countries analysed. In addition to the differentiation according to fuel, plant capacity and operating hours, differentiated limit values also apply to plants that were installed before 20 December 2018. Article 1.1.2 of the decree defines various age categories of existing plants and new plants.

5.4.1 Limit values

The limit values differentiate between existing plants that were authorised before 1993 and six categories of "new plants", depending on the date of the permit. Table 62 lists the categories for which limit values have been set for fuel oil and natural gas plants with a rated thermal input of up to 10 MW.

Table 62: Age categories of existing and new plants in Flanders

Plant group	Permit	Installation
Existing plant	before 1993	
New plant 1)	1993 - 1995	
New plant 2)	1996 - 2004	
New plant 3a)	2005 - 2009	
New plant 3b)	2010 - 2013	
New plant 4)	2014 - 19.12.2017	until 19.12.2018
New plant 5)	from 20.12.2017	from 20.12.2018

Source: VLAREM II (2022)

Limit values for liquid fuels are listed in Table 63 for the category 0.3 to 5 MW, and in Table 64 for the category with more than 5 MW.

Table 63: Emission limit values for medium combustion plants (1 - 5 MW) for liquid fuels (3 % O_2) in Flanders

Plant group	Capacity [MW]	NOx [mg/Nm³]	SO_2 [mg/Nm³]	Dust [mg/Nm³]	CO [mg/Nm³]	Nickel [mg/Nm³]	Vanadium [mg/Nm³]
Permit until 1992	0,3 - 5	650	1700	200	250	3	5
Permit 1993 - 1995	0,3 - 2	450	1700	100	175	3	5
Permit 1993 - 1995	≥ 2 - 5	600	1700	100	175	3	5
Permit 1996 - 2004	0,3 - 2	250	170	100	175	3	5
Permit 1996 - 2004	≥ 2 - 5	600	1700	100	175	3	5
Permit 2005 - 2013	0,3 - 2	185	170	100	175	3	5
Permit 2005 - 2013	≥ 2 - 5	525	1700	100	175	3	5
Permit 2014 - 19.12.17 and installed before 20.12.2018	0,3 - 5	185	170	5	175	3	5
Installed from 20.12.2018	0,3 - 5	185	170	5 (50)*	175	3	5

* The value in brackets applies to plants with less than 500 operating hours per year

Source: VLAREM II (2022)

The lowest NOx limit value for fuel oil of 185 mg/Nm³ applies to plants with 0.3 MW to 2 MW that were licensed from 1 January 2005. For larger plants with 2 MW to 5 MW, this relatively low limit value applies to plants licensed from 1 January 2014.

Table 64: Emission limit values for medium combustion plants (> 5 - 10 MW) for liquid fuels (oxygen content 3 %) in Flanders

Plant group	Capacity [MW]	NOx [mg/Nm³]	SO_2 [mg/Nm³]	Dust [mg/Nm³]	CO [mg/Nm³]	Nickel [mg/Nm³]	Vanadium [mg/Nm³]
Permit until 1992	> 5 - 10	650 (400)* (200)**	1700 (350)*	200	250	3	5
Permit 1993 - 2013	> 5 - 10	400 (200)**	1700 (350)*	50	175	3	5
Permit 2014 - 19.12.17 and installed before 20.12.2018	> 5 - 10	250 (200)**	170	10	175	3	5
Installed from 20.12.2018	> 5 - 10	200 (250)***	170	10 (50)***	175	3	5

* The value applies from 2025

** The value applies from 2025 for fuel oil

*** The value applies to plants with less than 500 operating hours per year

Source: VLAREM II (2022)

Limit values for natural gas plants are shown in Table 65 (0.3 - 5 MW) and Table 66 (> 5 MW).

Table 65: Emission limit values for medium combustion plants (0.3 - 5 MW) for natural gas (3 % O_2) in Flanders

Plant age	Performance [MW]	NOx [mg/Nm³]	SO_2 [mg/Nm³]	Dust [mg/Nm³]	CO [mg/Nm³]
Permit until 1992	0,3 - 5	150	35	50	250
Permit 1993 - 2009	0,3 - 5	150	35	5	100
Permit 2010 - 19.12.2017 and installation before 20.12.2017 or installation from 20.12.2018	0,3 - 5	80	35	5	100

Source: VLAREM II (2022)

For natural gas combustion plants in the 0.3 MW to 5 MW output category, the NO_x emission limit value of 80 mg/Nm³ already applies to plants permitted from 1 January 2010.

Table 66: Emission limit values for medium combustion plants (> 5 - 10 MW) for natural gas (3 % O_2) in Flanders

Plant age	Performance [MW]	NOx [mg/Nm³]	SO_2 [mg/Nm³]	Dust [mg/Nm³]	CO [mg/Nm³]
Permit until 1992	> 5 – 10	300	35	50	250
Permit 1993 - 1995	> 5 – 10	300	35	5	100
Permit 1996 - 2013	> 5 – 10	150	35	5	100
Permit 2014 - 19.12.2017 and installed before 20.12.2018 or installed from 20.12.2018	> 5 – 10	80	35	5	100

Source: VLAREM II (2022)

Stricter requirements will apply to fuel oil and natural gas combustion plants from 1 January 2030, which are not described here.

5.4.2 Measurements

The measurement period requirements for medium combustion plants with 1 MW to less than 50 MW are regulated in Flanders in Section 5.43.2 of the Decree (VLAREM 2022). Table 67 shows the periods for plants with a rated thermal input of 1 MW to less than 20 MW.

Table 67: Measurement periods for medium combustion plants (1 - < 20 MW) in Flanders

Capacity and annual operation	1 - < 5 MW and < 500 hours	5 - < 20 MW and < 500 hours	1 - < 5 MW and > 500 hours	5 - < 20 MW and > 500 hours
Measurement period	Every 5 years or after 1500 hours	Every 2 years	Every 2 years	Every 3 months

Source: VALREM II (2022)

The decree contains an open definition of the measurement duration(s). It allows a single measurement lasting one hour or ninety minutes. The average measurement value of all individual measurements must be calculated. The measurements must be carried out at a load that corresponds as closely as possible to the real situation.

5.4.3 Measurement uncertainty

The measurement uncertainty must not exceed 30 % of the measurement result for all parameters. The measurement uncertainty must be added to the measurement result. This requirement was reviewed in 2022. (UBA workshop 2022)

5.4.4 Techniques used and measured values

According to the competent authority, low NOx burners are the standard in Flanders. SCR and SNCR are used in larger combustion plants, but not in medium combustion plants with a rated thermal input of 1 MW to less than 10 MW. (UBA workshop 2022)

Current measurement values from oil- and gas-fired medium combustion plants with 1 - 10 MW in Flanders are not available (UBA workshop 2022). The last study on best available techniques applied in existing medium combustion plants in Flanders was carried out 20 years ago (Goovaerts et al. 2002). An estimate of emission values achievable with BAT in exclusively new plants was made in a study 10 years ago (Dils/Huybrechts 2012).

5.5 The Netherlands

The EU Directive on medium combustion plants (EU Directive 2015) is transposed into Dutch legislation by section 3.2.1. of the Decree on Environmental Management Activities ("Aktiviteitenbesluit milieubeheer") (Aktiviteitenbesluit 2022).

5.5.1 Limit values

Table 68 lists the limit values that apply to medium combustion plants with 1 MW to less than 20 MW in the Netherlands if they are operated with natural gas or liquid fuels.

The NO_x limit value of 70 mg/Nm³ is in force for newly installed plants since 1998. Since 2017, this limit value also applies to plants installed before 1998. Plants with less than 500 operating hours per year are exempt from the limit values. (UBA workshop 2022)

Table 68: Emission limit values for combustion plants 1 - < 20 MW (3 % O_2) in the Netherlands

Fuel	NO_x [mg/Nm³]	SO_2 [mg/Nm³]	Dust [mg/Nm³]
Natural gas	70	-	-
Liquid fuels	120	200	5

Source: Activity report (2022)

5.5.2 Measurements

Table 69 shows the required measurement periods for existing plants and for new plants. For existing plants, only one single measurement is required within the first four weeks after installation or when the emission limit values are updated. From 2025, a three-year measurement obligation will apply to existing plants from 5 MW, and from 2030 the three-year measurement obligation will also apply to plants with 1 MW to less than 5 MW.

Table 69: Measurement periods for medium combustion plants (1 - 20 MW) in the Netherlands

Plant type	New plant (as of 20.12.2018)	Existing plant 1 - < 5 MW	Existing plant ≥ 5 MW
< 2025	Every 3 years	Once a year	Once a year
From 2025	Every 3 years	Once a year	Every 3 years
From 2030	Every 3 years	Every 3 years	Every 3 years

Source: Infomil (2022)

An emission measurement comprises three half-hour measurements at a load of at least 60 %. This is particularly relevant for greenhouses with seasonal and crop-specific heat requirements. To ensure that this minimum is adhered to, the measurements should be planned accordingly.

Measurements in medium combustion plants must be carried out by certified measurement institutions in accordance with the "SCIOS Scope 6" standard. SCIOS, the "Certification system for the quality management system for carrying out maintenance and monitoring of technical installations" is a foundation that defines the rules for the monitoring of plants.[11] SCIOS records in a national database both the registration of medium combustion plants and the measurement results.

In the Netherlands, the competent authority (local authority or environment agency) is responsible for checking compliance with the limit values.

5.5.3 Measurement uncertainty

The limit values are complied with if none of the results of the individual measurements after deduction of the measurement uncertainty is equal to or lower than the emission limit value.

The maximum permissible measurement uncertainty for each parameter is shown in Table 70.

Table 70: Maximum measurement uncertainties in the Netherlands

Pollutant	Maximum measurement uncertainty
NOx	20 %
SO_2	20 %
Dust	30 %

Source: Bal (2022)

5.5.4 Techniques used and measured values

Low NO_x burners are the standard in existing and new plants. Their operation contributes decisively to compliance with the NO_x limit value of 70 mg/Nm³, whereby the measurement uncertainty is deducted from the measured value allowing a maximum uncertainty of 20 %.

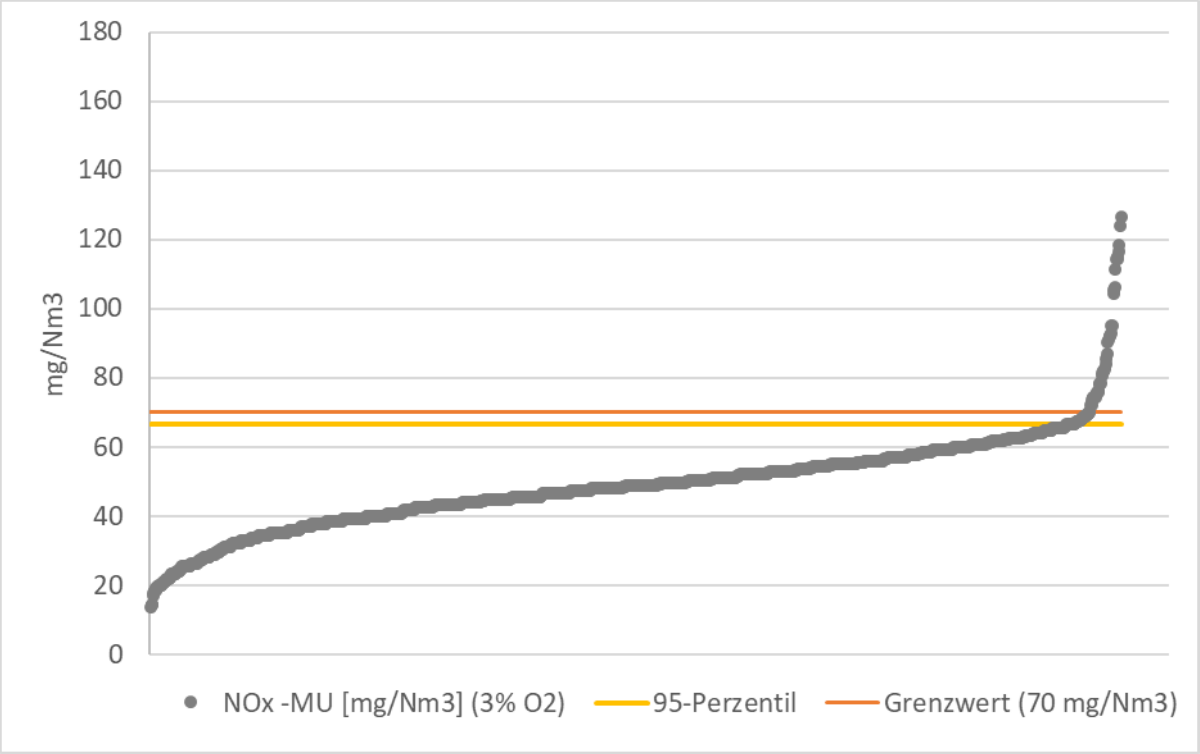
The following three figures show NO_x measured values from 1140 Dutch medium combustion plants (all fired with natural gas). The figures are based on an extract from the SCIOS database with measured values from 2017, when the limit value of 70 mg/Nm³ also had become valid for existing plants.

Figure 64 corresponds to the compliance practice in the Netherlands, i.e. the maximum allowed measurement uncertainty of 20 % was subtracted from the measured values for comparison with the limit value of 70 mg/Nm³ (the real measurement uncertainties are generally lower, as documented for more recent measurement values in the SCIOS database since 2022). The 95 percentile of the measured values is 66.4 mg/Nm³, i.e. 95 % of the measured values comply with the limit value when the maximum permissible measurement uncertainty is fully utilised.

If the maximum permissible measurement uncertainty of 20 % is added to the measured values, this results in a 95 percentile of 96.9 mg/Nm³ (Figure 65). This conversion of the measured values corresponds to the requirement for compliance check with the limit values in Germany. The limit value setting of 70 mg/Nm³ with a subtraction of the measurement uncertainty thus corresponds approximately to a limit value setting of 100 mg/Nm³ if an addition of the measurement uncertainty is required.

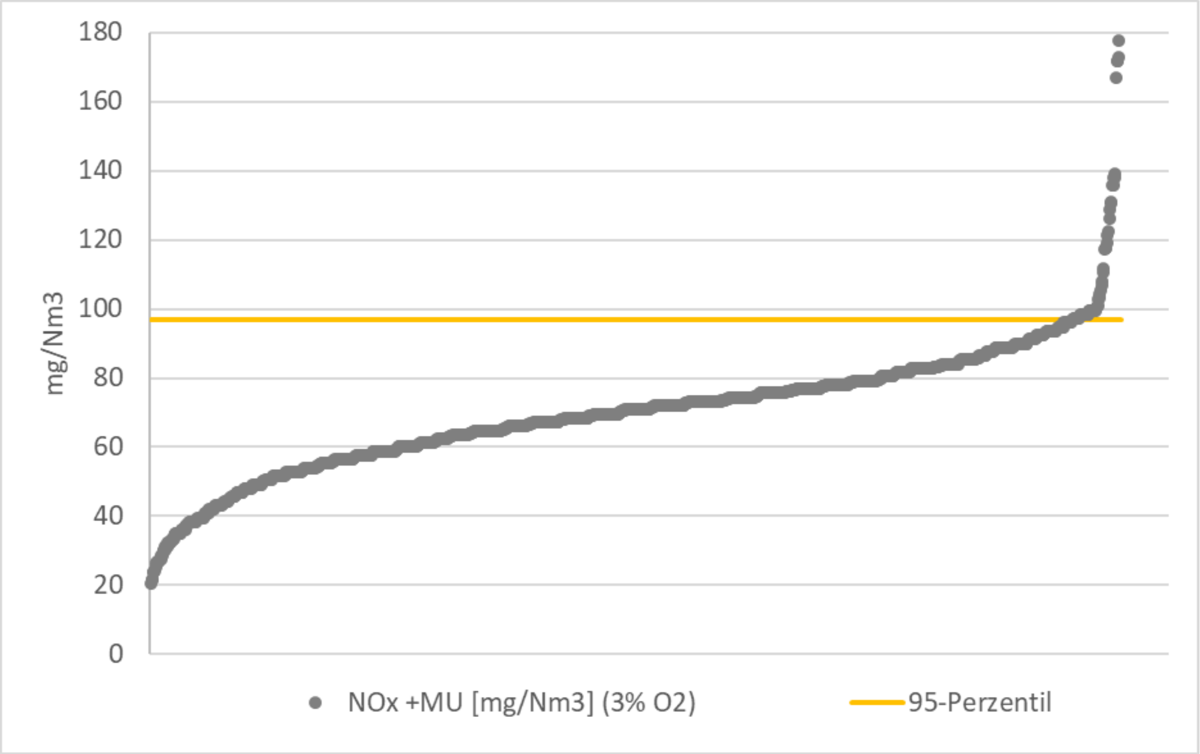
[11] SCIOS: https://www.scios.nl/

Figure 64: NOx emission values in natural gas plants (1 to 10 MW) in the Netherlands after subtraction of the maximum permissible measurement uncertainty (n = 1140)



Source: SCIOS (2022)

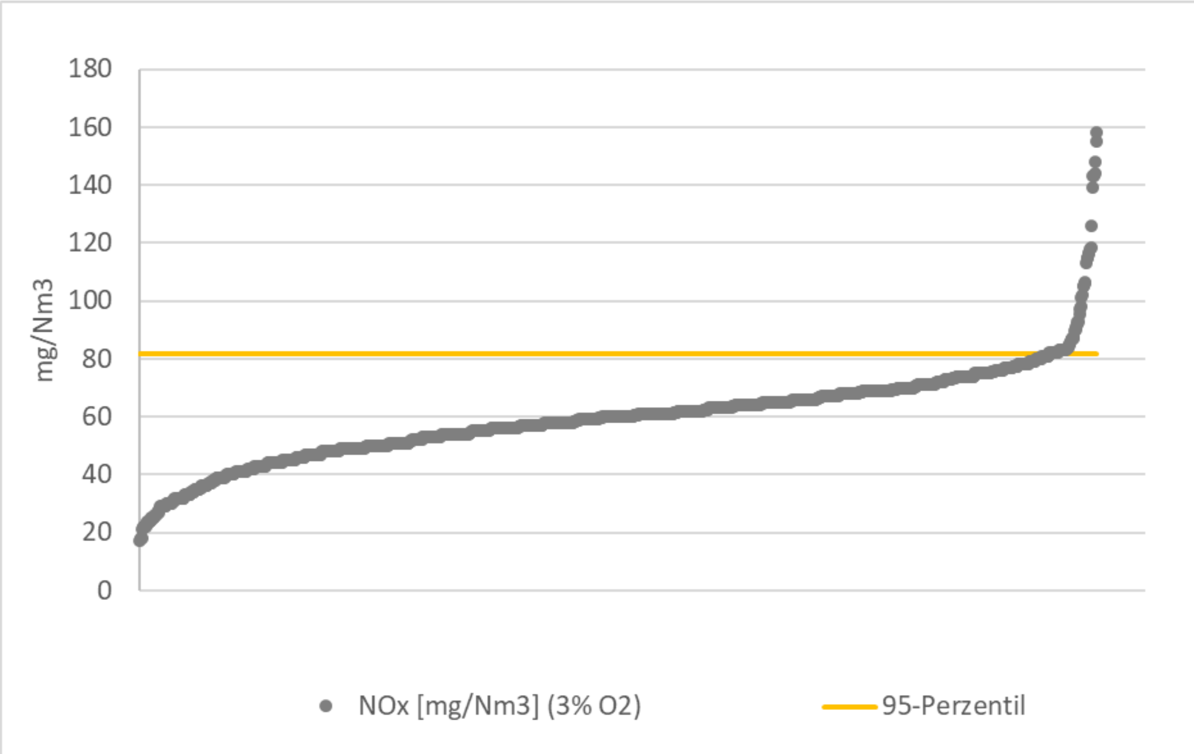
Figure 65: NOx measurement values from natural gas plants (1 to 10 MW) in the Netherlands after adding the maximum permissible measurement uncertainty of 20 % (n = 1140)



Source: SCIOS (2022)

If no measurement uncertainty is considered for the measured values, the 95 percentile of the measured values is 81.8 mg/Nm³ (Figure 66). This approach to compare with the limit value corresponds to the requirement in Denmark (no consideration of measurement uncertainty).

Figure 66: NOx emission values of natural gas plants (1 to 10 MW) in the Netherlands without taking measurement uncertainty into account (n = 1140)

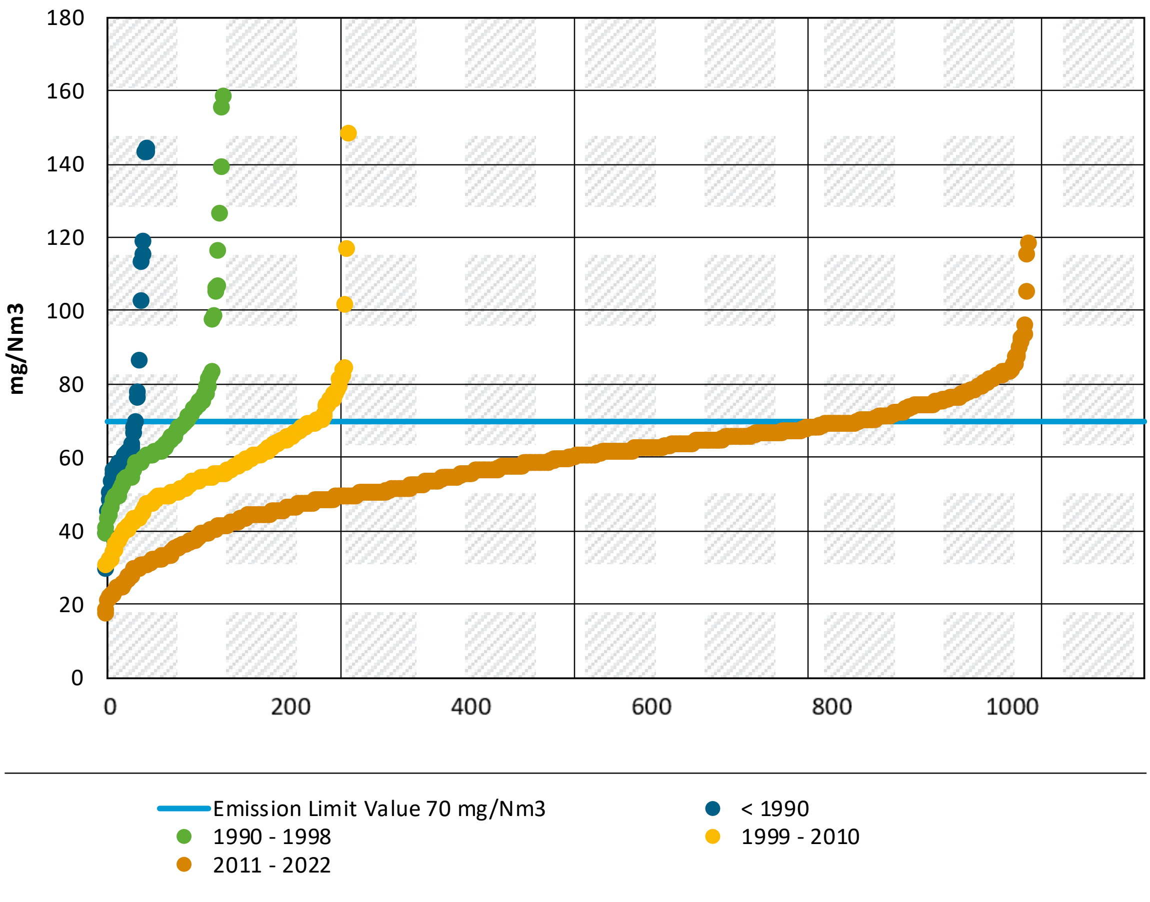


Source: SCIOS (2022)

Figure 67 shows the emission values after deduction of the measurement uncertainty, sorted by age group of commissioning. For each age group, the vast majority of measurements is below the NO_x limit value of 70 mg/Nm³.

The 95th percentile in the graph roughly marks the point at which the curve of the measured values rises steeply and exceeds the limit value by more than a small amount. The emission level has fallen in newer plants due to the use of low NO_x burners. For example, the lowest NO_x values of the category "1990 - 1998" are around 40 mg/Nm³, and the lowest values of the category "2011 - 2022" are around 20 mg/Nm³.

Figure 67: NO_x emission values from natural gas plants (1 - < 10 MW) in the Netherlands minus measurement uncertainty and sorted by four age groups (n = 1140)



Source: SCIOS (2022)

5.6 Austria

In Austria, the EU Directive (2015) was transposed into national legislation by the Combustion Plant Ordinance (FAV 2019). Steam boilers and waste heat boilers are regulated separately by the Emissions Protection Act for Boiler Plants (EG-K) (EG-K 2015).

5.6.1 Limit values

Table 71 shows the emission limit values in force in Austria. For NO_x, different limit values apply, depending on the capacity. Federal state authorities are responsible for monitoring the plants.

Table 71: Emission limit values for combustion plants 0.1 - 50 MW (3 % O_2) in Austria

Firing	Type	Performance [MW]	NO_x [mg/Nm³]	CO [mg/Nm³]	Dust [mg/Nm³]
Natural gas	Existing	0,1 - 3	120[12]	80	-
		> 3	100[13]	80	-
	New	≥ 1	100	80	-
Fuel oil	Existing	1 - 2	150 *	80	-
		> 2 - ≤ 5	150*	80	20
		> 5	150*	80	20**
	New	1 - 2	150*	80	-
		> 2	150*	80	20**

* 200 mg/Nm³ for extra-light fuel oil, extra-light fuel oil with low sulphur content, extra-light fuel oil with biogenic components and liquid standardised biogenic fuels, in each case in high-temperature processes or with preheated combustion air

**10 mg/Nm³ for fuel oil extra light low sulphur

Source: FAV (2019)

5.6.2 Measurements

Plants with a capacity of 1 MW to less than 20 MW must be tested at least every three years as shown in Table 72. The FAV (2019) requires periodic measurements of NO_x, dust, CO and (if equipped with NO_x reduction technique) NH_3. The requirement comprises three half-hourly individual measurements, which must be carried out within three hours and at normal load.

Table 72: Measurement periods for medium combustion plants (1 - < 20 MW) in Austria

1- ≤ 2 MW	> 2 MW
Every 5 years	Every 3 years

Source: FAV (2019)

There is neither a database nor reliable information on emission reduction techniques at national level. In general, it is assumed that low NOx burners and air staging are common techniques. SCR and SNCR are occasionally used in larger plants but are not common in plants from 1 MW to less than 10 MW.

5.6.3 Measurement uncertainty

The maximum permissible measurement uncertainty for each parameter is shown in Table 73. The measurement uncertainty must not exceed the specified maximum value as a proportion of

[12] 200 mg/m³ for high-temperature processes or with preheated combustion air

[13] 200 mg/m3 for high-temperature processes or with preheated combustion air

the respective emission limit value. To check compliance with the limit value, the measurement uncertainty must be subtracted from each individual value and compared with the limit value.

Table 73: Maximum permissible measurement uncertainty in Austria

Parameters	Maximum measurement uncertainty
CO	10 %
NO_x	20 %
Dust	30 %
NH_3	40 %

Source: FAV (2019)

5.6.4 Techniques used and measured values

Information on the reduction techniques used and current measured values is not available at the Austrian German Environment Agency, as the federal states are responsible for monitoring, and there is no central database. (UBA workshop 2022)

5.7 Switzerland

As Switzerland is not a member of the European Union, the EU Directive (2015) did not have to be transposed into national law.

The regulation on medium combustion plants therefore deviates from the European regulation. The plants are regulated by the Clean Air Ordinance (LRV 2022), which is supplemented by the publication of emission measurement recommendations (FOEN 2020).

In Switzerland, low NOx burners and exhaust gas recirculation are the standard techniques.

The majority of plants are equipped with dual-fuel burners; a trend towards switching from natural gas to fuel oil was observed in 2022.

For fuel oil combustion plants with an output of less than 5 MW, the use of heavy fuel oil with a sulphur content of up to 2.8 % as fuel is prohibited. For these plants, the use of "EL fuel oil" (max. 0.1 % S content) will also be prohibited from 1 June 2023. The "eco fuel oil" grade (0.005 % S content) is already predominantly used in fuel oil plants. This grade corresponds to the "EL low-sulphur fuel oil" grade with a maximum sulphur content of 50 mg/kg. In addition, the Swiss standard for fuel oil (SN 181160-2) had also limited the nitrogen content to 100 mg/kg - unlike the "low-sulphur, low-nitrogen fuel oil" grade introduced in the DIN standard in September 2020, which limits the nitrogen content to 140 mg/kg. However, the nitrogen limit was removed from the Swiss standard in 2019, as fuel oil deliveries generally came from the EU market, where this grade does not exist. This made monitoring difficult and led to problems at customs.

5.7.1 Limit values

Emission limit values are specified for the parameters CO, smoke number, NO_x and ammonia (if equipped with NO_x reduction technique).

Table 74: Emission limit values for combustion plants < 10 MW (3 % O_2) in Switzerland

Fuel type	NOx [mg/Nm³]	CO [mg/Nm³]	NH_3 [mg/Nm³]	Smoke number
Natural gas	80*	100	30	-
Fuel oil	120**	80	30	1

* 110 mg/m³ for plants with a heating medium temperature of over 110 °C and 200 mg/m³ for bright radiators and dark radiators

** 150 mg/m³ for plants with a heating medium temperature of over 110 °C and 200 mg/m³ for bright radiators and dark radiators

Source: LRV (2022)

5.7.2 Measurements

For medium combustion plants with an output of 1 MW to less than 10 MW, compliance with the limit values must be checked every one to two years. The regional ("cantonal") authorities are responsible for monitoring.

Table 75: Measurement periods for medium combustion plants (1 - < 10 MW) in Switzerland

Natural gas and fuel oil ≤ 5 MW	Natural gas and fuel oil > 5 - < 10 MW and max. 3000 operating hours per year*	Natural gas and fuel oil > 5 - < 10 MW and 3000 or more operating hours per year*
Every 2 years	Every 2 years	Once a year

* As a moving average over a period of five years

Source: LRV (2022)

A compliance check comprises three half-hour measurements under different load conditions, the average value of which is used to check compliance.

No load conditions are specified for the measurement. The measurement must be carried out at the highest expected emission. (UBA workshop 2022)

5.7.3 Measurement uncertainty

In Switzerland, the measurement uncertainty is subtracted from the measured value when checking compliance with the limit value.

5.7.1 Techniques used and measured values

Information on the reduction techniques used and on current measured values is not available at the Swiss Federal Office for the Environment, as the regional ("cantonal") authorities are responsible for monitoring, and no central database exists. (UBA workshop 2022)

6 List of references

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A List of plants (anonymised)

Table 76 (fuel oil) and Table 77 (natural gas) document for the plants measured, the federal states in which the plants are located, equipment with multi-fuel or single-fuel burner, the period of installation and the range of the nominal heat output.

Table 76: Measured fuel oil plants

Measure-ment No.	Plant location - federal state	Plant No	Multi-fuel burner	Installation period	Nominal heat output [MW]
1	Saxony	1	Yes	01.01.1990 until 31.12.1994	5 - < 10
2	Saxony	2	Yes	01.01.1990 until 31.12.1994	5 - < 10
3	Saxony	3	Yes	01.01.1990 to 31.12.1994	2 - < 3
4	Thuringia	4	Yes	01.01.1990 to 31.12.1994	2 - < 3
5	Thuringia	5	No	01.01.1995 until 31.12.1999	5 - < 10
6	Brandenburg	6	No	01.01.1990 to 31.12.1994	3 - < 4
7	Brandenburg	7	Yes	01.01.1990 to 31.12.1994	5 - < 10
8	Saxony	10	No	01.01.1990 to 31.12.1994	1 - < 2
9	Saxony-Anhalt	11	No	01.01.1995 until 31.12.1999	1 - < 2
10	Saxony-Anhalt	12	No	01.01.1995 until 31.12.1999	1 - < 2
11	Saxony	15	Yes	01.01.2015 until 31.12.2019	2 - < 3
12	Saxony	18	Yes	01.01.1990 to 31.12.1994	1 - < 2
13	Saxony	19	Yes	01.01.1990 to 31.12.1994	2 - < 3
14	Saxony	21	No	01.01.1990 to 31.12.1994	1 - < 2
15	Saxony	22	Yes	01.01.1990 to 31.12.1994	4 - < 5
16	Saxony	23	Yes	01.01.1990 to 31.12.1994	4 - < 5
17	Saxony	25	Yes	01.01.1995 until 31.12.1999	4 - < 5
18	Saxony	29	Yes	01.01.1990 to 31.12.1994	4 - < 5
19	Saxony	30	Yes	01.01.1990 to 31.12.1994	4 - < 5
20	Saxony	31	Yes	01.01.1990 to 31.12.1994	1 - < 2
21	Saxony	32	Yes	01.01.1990 to 31.12.1994	1 - < 2
22	Saxony	33	Yes	01.01.1990 to 31.12.1994	1 - < 2
23	Saxony	34	Yes	01.01.1990 to 31.12.1994	1 - < 2

Measure-ment No.	Plant location - federal state	Plant No	Multi-fuel burner	Installation period	Nominal heat output [MW]
24	Saxony	35	Yes	01.01.1990 to 31.12.1994	1 - < 2
25	North Rhine-Westphalia	52	Yes	01.01.2010 until 31.12.2014	1 - < 2
26	North Rhine-Westphalia	53	Yes	01.01.2010 until 31.12.2014	2 - < 3
27	Bavaria	55	Yes	01.01.2010 until 31.12.2014	1 - < 2
28	Hamburg	62	No	01.01.1985 to 31.12.1989	5 - < 10

Table 77: Measured plants natural gas operation

Measure-ment No.	Plant location - federal state	Plant No.	Multi-fuel burner	Installation period	Nominal heat output [MW]
29	Saxony	1	Yes	01.01.1990 to 31.12.1994	5 - < 10
30	Saxony	2	Yes	01.01.1990 to 31.12.1994	5 - < 10
31	Saxony	3	Yes	01.01.1990 to 31.12.1994	2 - < 3
32	Thuringia	4	Yes	01.01.1990 to 31.12.1994	2 - < 3
33	Brandenburg	7	Yes	01.01.1990 to 31.12.1994	5 - < 10
34	Saxony	8	No	01.01.1975 to 31.12.1979	2 - < 3
35	Saxony	9	No	01.01.1975 to 31.12.1979	2 - < 3
36	Saxony	13	No	01.01.2015 until 31.12.2019	4 - < 5
37	Saxony	14	No	01.01.1995 until 31.12.1999	4 - < 5
38	Saxony	15	Yes	01.01.2015 until 31.12.2019	2 - < 3
39	Saxony	16	No	01.01.1995 until 31.12.1999	1 - < 2
40	Saxony	17	No	01.01.1995 until 31.12.1999	1 - < 2
41	Saxony	18	Yes	01.01.1990 to 31.12.1994	1 - < 2
42	Saxony	19	Yes	01.01.1990 to 31.12.1994	2 - < 3
43	Saxony	20	No	01.01.1990 to 31.12.1994	2 - < 3
44	Saxony	22	Yes	01.01.1990 to 31.12.1994	4 - < 5
45	Saxony	23	Yes	01.01.1990 to 31.12.1994	4 - < 5
46	Saxony	24	No	01.01.1995 until 31.12.1999	4 - < 5

Measure-ment No.	Plant location - federal state	Plant No.	Multi-fuel burner	Installation period	Nominal heat output [MW]
47	Saxony	25	Yes	01.01.1995 until 31.12.1999	4 - < 5
48	Saxony	26	No	01.01.1980 to 31.12.1984	2 - < 3
49	Saxony	27	No	01.01.1980 to 31.12.1984	2 - < 3
50	Saxony	28	No	01.01.1990 to 31.12.1994	2 - < 3
51	Saxony	29	Yes	01.01.1990 until 31.12.1994	4 - < 5
52	Saxony	30	Yes	01.01.1990 until 31.12.1994	4 - < 5
53	Saxony	31	Yes	01.01.1990 to 31.12.1994	1 - < 2
54	Saxony	32	Yes	01.01.1990 to 31.12.1994	1 - < 2
55	Saxony	33	Yes	01.01.1990 until 31.12.1994	1 - < 2
56	Saxony	34	Yes	01.01.1990 until 31.12.1994	1 - < 2
57	Saxony	35	Yes	01.01.1990 to 31.12.1994	1 - < 2
58	Brandenburg	36	No	01.01.2005 until 31.12.2009	1 - < 2
59	Brandenburg	37	No	01.01.2005 until 31.12.2009	1 - < 2
60	Brandenburg	38	No	01.01.2005 until 31.12.2009	1 - < 2
61	Brandenburg	39	No	01.01.2010 until 31.12.2014	1 - < 2
62	Brandenburg	40	No	01.01.2015 until 31.12.2019	1 - < 2
63	Brandenburg	41	No	01.01.1995 until 31.12.1999	1 - < 2
64	Saxony-Anhalt	42	No	01.01.2000 until 31.12.2004	4 - < 5
65	Saxony-Anhalt	43	No	01.01.2015 until 31.12.2019	2 - < 3
66	Saxony-Anhalt	44	No	01.01.2000 until 31.12.2004	5 - < 10
67	Saxony-Anhalt	45	No	01.01.2000 until 31.12.2004	5 - < 10
68	Brandenburg	46	No	01.01.1990 to 31.12.1994	1 - < 2
69	Brandenburg	47	No	01.01.2010 until 31.12.2014	1 - < 2

Measure-ment No.	Plant location - federal state	Plant No.	Multi-fuel burner	Installation period	Nominal heat output [MW]
70	Berlin	48	No	01.01.2000 until 31.12.2004	1 - < 2
71	Berlin	49	No	01.01.2000 until 31.12.2004	1 - < 2
72	North Rhine-Westphalia	50	No	01.01.2010 until 31.12.2014	1 - < 2
73	North Rhine-Westphalia	51	No	01.01.2010 until 31.12.2014	1 - < 2
74	North Rhine-Westphalia	52	Yes	01.01.2010 until 31.12.2014	1 - < 2
75	North Rhine-Westphalia	53	Yes	01.01.2010 until 31.12.2014	2 - < 3
76	Bavaria	54	No	01.01.1995 until 31.12.1999	1 - < 2
77	Bavaria	55	Yes	01.01.2010 until 31.12.2014	1 - < 2
78	Bavaria	56	No	01.01.2010 until 31.12.2014	2 - < 3
79	Hesse	57	No	01.01.2015 until 31.12.2019	3 - < 4
80	Hamburg	58	No	01.01.2010 until 31.12.2014	4 - < 5
81	Hamburg	59	No	01.01.2010 until 31.12.2014	4 - < 5
82	Hamburg	60	No	After 01.01.2020	5 - < 10
83	Hamburg	61	No	After 01.01.2020	5 - < 10
84	North Rhine-Westphalia	63	No	01.01.1990 until 31.12.1994	2 - < 3
85	North Rhine-Westphalia	64	No	01.01.1990 until 31.12.1994	2 - < 3
86	North Rhine-Westphalia	65	No	01.01.2015 until 31.12.2019	2 - < 3
87	North Rhine-Westphalia	66	No	01.01.2015 until 31.12.2019	2 - < 3
88	North Rhine-Westphalia	67	No	01.01.2015 until 31.12.2019	3 - < 4
89	North Rhine-Westphalia	68	No	01.01.2015 until 31.12.2019	3 - < 4
90	North Rhine-Westphalia	69	No	01.01.2005 until 31.12.2009	3 - < 4

Measure-ment No.	Plant location - federal state	Plant No.	Multi-fuel burner	Installation period	Nominal heat output [MW]
91	Saxony-Anhalt	70	No	01.01.2010 until 31.12.2014	1 - < 2
92	Saxony-Anhalt	71	No	01.01.2005 until 31.12.2009	1 - < 2
93	Saxony-Anhalt	72	No	01.01.2010 until 31.12.2014	3 - < 4
94	Saxony-Anhalt	73	No	01.01.2010 until 31.12.2014	3 - < 4
95	Saxony-Anhalt	74	No	01.01.2015 until 31.12.2019	1 - < 2
96	Saxony	75	No	01.01.1990 to 31.12.1994	5 - < 10
97	Saxony	76	No	01.01.1990 to 31.12.1994	5 - < 10
98	Lower Saxony	77	No	01.01.1985 to 31.12.1989	5 - < 10
99	Lower Saxony	78	No	01.01.1995 until 31.12.1999	4 - < 5
100	Saxony-Anhalt	79	No	01.01.2000 until 31.12.2004	3 - < 4

B Operator questionnaire

Figure 68 shows the questionnaire completed by the operators for each plant.

Figure 68: Operator questionnaire

Data on person completing the form

Surname		
First name		
Company:		
Phone:		
Email:		
Date:		

1. Classification

1.1 Technical purpose of the plant:		*(e.g. hot water)*
1.2 Burner and abatement technique of the plant:		
1.3 Fuel(s):	Gas- / Oil- / Others / Mixed	
Fuel description:		*(e.g. low-sulphur heating oil)*
1.4 Putting the plant into operation:		*Date or year*
1.5 Sector		
Economic sector:		
NACE-CODE:		
1.6 Plant combined with other plant (at the site)?		

2. Operating performance

2.1 Plant output in MW:		*MW*
2.2 Annual fuel use:		*L*
		m3
		kg
2.3 Annual operating hours (approx.):		*Hours per year*
2.3.1 of which full-load operating hours:		*Hours per year*
2.3.2 of which part-load operating hours:		*Hours per year*
2.4 Typical operation during the course of the day, week and year?		*Course of the day*
		Course of the week
		Course of the year

3. Maintenance

3.1 Maintenance interval:		*Weeks*
3.2 Last maintenance:		*Date or month/year*

4. Emission reduction

4.1 Emission-relevant retrofits:		*(e.g. low NOx burner, lambda sensor)*
4.2 Emission reduction techniques used:		*(e.g. catalyst)*
4.3 Height of chimney outlet above ground level:		*Meter*
4.4 Setting values of the (nitrogen oxides) safety device:		*According to technical instructions air 2002*

Source: own figure (Ökopol), translated from German

C Measurement protocol (example)

Figure 69 to Figure 71 show an example of a measurement protocol.

Figure 69: Measurement protocol of a plant (part 1)

Plant number 1

Measurement results in gases

Installation:		XX					
Plant form completed by							
First name:		Andreas					
Surname:		Mustermann					
Company:		XY GmbH					
Phone:							
Email:		andreas.mustermann@xy-power.de					
Date:		03.12.2020					
Plant:		Gas-oil boiler 1					
Manufacturer name:		Boiler X					
Type							
Year of manufacture:		1994					
Permissible operating overpressure (bar):		8,0					
Permissible steam production (t/h):							
Permissible hot steam temperature (C°):							
Permissible flow temperature (C°):		120					
Permissible heat output (MW):		6,0					
Technical purpose:		Heat generation					
Fuel(s):		Heating oil + gas					
Commissioning of the plant		1995					
Economic sector:		Energy industry	Predominantly residential (80%) / subordinately commercial				
Combined with other plants:		CHP					
Annual fuel use:		0 L					
		392333 Nm3					
Annual operating hours:		2.500					
of which full-load operating:			Base load mainly with CHP unit, peak load with boiler				
of which part-load operating:							
Typical operating behaviour:		Outdoor temperature regulation					
Maintenance interval:		Annually					
Last maintenance:		Jan 20					
Emission-relevant retrofits:							
Emission reduction techniques used:							
Height of chimney outlet above ground level:		25m					
Nitrogen oxides safety device:							
Burner							
Manufacturer name:							
Burner type:		Burning material xy					
Year of manufacture:							
Power min. (kW):							
Power max. (kW):							
Connection pressure min. (mbar):							
Max. connection pressure (mbar):							
Fuel oil EL type min. (kg/h):							
Fuel oil EL type max. (kg/h):							
Measurement location:		Horizontal flue gas pipe					
File number:		K-MS-8597-20					
Measurement performed by:		Dipl.-Ing. XY					
Report created by:		Dipl.-Ing. XY					
Measurement number:		1	2	3	4	5	6
Fuel type:		Natural gas	Natural gas	Natural gas	Fuel oil	Fuel oil	Fuel oil
Operating status:					62 % (3.7 MW)	58 % (3.5 MW)	60 % (3.6 MW)
Measuring day:		30.11.2020	30.11.2020	30.11.2020	30.11.2020	30.11.2020	30.11.2020
Exhaust gas conditions							
Measurement start		08:52	09:51	10:31	11:33	13:10	14:00
Barometer reading	mbar	1 008	1 008	1 008	1 008	1 008	1 008
Duct temperature	°C	129	120	124	132	141	133
Stat. pressure in duct	mbar	0,15	0,18	0,21	0,59	0,56	0,41
Water vapor pressure	mbar	186,4	186,4	186,4	120,9	120,9	120,9
Humidity	Vol. %	18,5	18,5	18,5	12,0	12,0	12,0
Dew point	°C	58,6	58,6	58,6	49,6	49,6	49,6
Oxygen content	Vol. %	4,13	3,87	4,36	5,28	5,70	5,36
Average velocity	m/s	8,2	7,5	7,7	11,9	12,6	12,7
Duct cross-section	m²	0,238	0,238	0,238	0,238	0,238	0,238
Volume flow rate standardized dry	m³/h	3 841	3 603	3 677	6 006	6 232	6 394

Source: own figure (Mattersteig), English translation (Ökopol)

Figure 70: Measurement protocol of a plant (part 2)

Carbon monoxide and nitrogen oxides							
Limit of quantification	**CO**	**3 mg/m^3**					
Limit of quantification	**NOx**	**6 mg/m^3**					
Measurement uncertainty	**CO**	**8 %**					
Measurement uncertainty	**NOx**	**8 %**					
Measurement time from:		**09:11**	**09:55**	**10:41**	**11:55**	**13:20**	**14:09**
Measurement time to:		**09:41**	**10:25**	**11:11**	**12:40**	**13:59**	**14:41**
Measurement interruptions:		**00:00**	**00:00**	**00:00**	**00:19**	**00:18**	**00:11**
Effective duration of measurements:		**00:30**	**00:30**	**00:30**	**00:26**	**00:21**	**00:21**
Concentration standardised dry							
Carbon monoxide	**mg/m^3**	**0.96**	**0.86**	**0.79**	**1.65**	**1.53**	**1.84**
Nitrogen oxides (NOx as NO2)	**mg/m^3**	**167.82**	**167.49**	**168.57**	**190.18**	**189.96**	**188.92**
Concentration standardised, O2 reference							
Oxygen reference value	Vol.-%	3.00					
O2 content during sampling	Vol.-%	4.13	4.21	4.12	5.35	5.34	5.36
Carbon monoxide	mg/m^3	1.02	0.92	0.85	1.90	1.76	2.12
Nitrogen oxides (NOx as NO2)	mg/m^3	179.09	179.61	179.75	218.69	218.33	217.40
TOC							
Limit of quantification	**C_{total}**	**1.5 mg/m^3**					
Measurement uncertainty	**C_{total}**	**15 %**					
Measurement time from:		**09:11**	**09:55**	**10:41**	**11:55**	**13:20**	**14:09**
Measurement time to:		**09:41**	**10:25**	**11:11**	**12:40**	**13:59**	**14:41**
Measurement interruptions:		**00:00**	**00:00**	**00:00**	**00:19**	**00:18**	**00:11**
Effective duration of measurements:		**00:30**	**00:30**	**00:30**	**00:26**	**00:21**	**00:21**
Concentration standardised dry							
C_{total}	**mg/m^3**	**0.82**	**0.60**	**0.59**	**0.60**	**0.57**	**0.60**
Concentration standardised, O2 reference							
Oxygen reference value	Vol.-%	3.00					
O2 content during sampling	Vol.-%	4.13	4.21	4.12	5.35	5.34	5.36
C_{total}	mg/m^3	0.88	0.65	0.63	0.68	0.65	0.69
Methane							
Limit of quantification	**CH_4**	**1.5 mg/m^3**					
Measurement uncertainty	**CH_4**	**18 %**					
Measurement time from:		**09:11**	**09:55**	**10:41**	**11:55**	**13:20**	**14:09**
Measurement time to:		**09:41**	**10:25**	**11:11**	**12:40**	**13:59**	**14:41**
Measurement interruptions:		**00:00**	**00:00**	**00:00**	**00:19**	**00:18**	**00:11**
Effective duration of measurements:		**00:30**	**00:30**	**00:30**	**00:26**	**00:21**	**00:21**
Concentration standardised dry							
Methane	**mg/m^3**	**0.79**	**0.79**	**0.79**	**0.73**	**0.73**	**0.73**
Concentration standardised, O2 reference							
Oxygen reference value	Vol.-%	3.00					
O2 content during sampling	Vol.-%	4.13	4.21	4.12	5.35	5.34	5.36
Methane	mg/m^3	0.84	0.85	0.84	0.84	0.84	0.84

Source: own figure (Mattersteig), English translation (Ökopol)

Figure 71: Measurement protocol of a plant (part 3)

Dust							
Limit of quantification	Stb	0,2 mg/m³					
Measurement uncertainty	Stb	0,3 mg/m³					
Measurement time from:		09:11	09:55	10:41	11:55	13:20	14:09
Measurement time to:		09:41	10:25	11:11	12:34	13:59	14:41
Measurement interruptions:		00:00	00:00	00:00	00:17	00:18	00:11
Effective duration of measurements:		00:30	00:30	00:30	00:22	00:21	00:21
Concentration standardised dry							
Dust	mg/m³	< 0,40	< 0,41	< 0,41	< 0,45	0,62	0,59
Concentration standardised, O2 reference							
Oxygen reference value	Vol.-%	3,00					
O2 content during sampling	Vol.-%	4,13	4,21	4,12	5,35	5,34	5,36
Dust	mg/m³	< 0,43	< 0,44	< 0,44	< 0,51	0,72	0,68
Smoke number							
Measurement time from:					12:43	12:57	14:46
Measurement time to:					12:46	13:00	14:49
Smoke number					0,16	0,06	0,01
Mass flows							
Volume flow	m³ i.N./h	3841	3603	3677	6006	6232	6394
Carbon monoxide	kg/h	0,004	0,003	0,003	0,010	0,010	0,012
Nitrogen oxides (NOx as NO2)	kg/h	0,64	0,60	0,62	1,14	1,18	1,21
TOC	kg/h	0,003	0,002	0,002	0,004	0,004	0,004
Methane	kg/h	0,003	0,003	0,003	0,004	0,005	0,005
Dust	kg/h	< 0,002	< 0,001	< 0,002	< 0,003	0,004	0,004

Measuring conditions at the measuring cross-section:	MEASURED VALUE	ACTUAL	TARGET	Recommendation of DIN EN 15259
Exhaust pipe diameter:	0,6 m			
Channel cross-section:	0,238 m²			
Undisturbed inlet section:	2,2 m	4.0 x diameter	5.0 x diameter	not fulfilled
Undisturbed outlet section:	3,1 m	5.6 x diameter	2.0 x diameter	fulfilled
Outlet to the outside:	> 5,0 m	> 9.1 x diameter	5.0 x diameter	fulfilled
Angle of gas flow to exhaust duct centerline		< 15°	< 15°	fulfilled
Local flow		non-negative	non-negative	fulfilled
Ratio of highest/lowest local velocity	2,6	< 3:1	< 3:1	fulfilled
Number of measurement axes		1	2	
Number of measuring points per axis		6	2	
Total number of measuring points		6	4	

If the dimensions given here for the length of the undisturbed inlet and outlet section are not met, this does not mean that this measuring section is à priori unsuitable. Rather, the criteria for the flow angle, flow direction and velocity distribution in the measurement cross-section (corresponding to the requirements of points 6.2.1 c 1) to 4) of DIN EN 15259) are decisive as to whether representative measurements of the volume flow and the mass concentration of the air pollutants are possible in the measurement cross-section.

The number of measurement axes was limited by the number of available measuring nozzles. All parameters were therefore measured on one axis at a time. The total number of measuring points in the measurement cross-section, on the other hand, was increased. This compensates for any increased measurement uncertainty resulting from non-optimal measurement conditions.

Special features during the measurements:

The boiler system was temperature-controlled according to the heat demand.
In particular during fuel oil operation, the burner was switched off several times due to inadequate heat consumption by the heating network.
The measurements were stopped during these downtimes. The results refer to times with burner operation.

Source: own figure (Mattersteig), English translation (Ökopol)

D Measurement results (standardised, based on 3 % O_2) as arithmetic mean of three individual measurements

Table 78: Measurement results and measurement uncertainties of fuel oil plants (average of three consecutive measurements, generally 30 minutes each)

No.	Load	CO [mg/m³]	Uncer-tainty [mg/m³]	NO_x as NO_2 [mg/m³]	Uncer-tainty [mg/m³]	TOC [mg/m³]	Uncer-tainty [mg/m³]	Methane [mg/m³]	Uncer-tainty [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Uncer-tainty [mg/m³]	Smoke number	Uncer-tainty
1	69 %	**1.924**	0.154	218.139	17.451	0.674	0.101	0.840	0.151	0.044	0.635	0.300	0.077	0.012
2	37 %	**0.895**	0.072	104.418	8.353	0.551	0.083	0.513	0.092	0.166	0.601	0.300	0.293	0.047
3	100 %	**4.678**	0.374	196.395	15.712	0.274	0.041	0.288	0.052	0.058	0.709	0.300	0.367	0.059
4	67 %	**4.196**	0.336	80.892	6.471	0.536	0.080	0.418	0.075	0.223	0.505	0.300	0.093	0.015
5	31 %	**4.301**	0.344	155.941	12.475	0.733	0.110	0.338	0.061	0.480	3.022	0.300	0.488	0.079
6	67 %	**3.934**	0.315	198.695	15.896	0.842	0.126	1.192	0.214	-0.051	0.095	0.300	0.040	0.006
7	10 %	**3.750**	0.300	120.462	9.637	2.687	0.403	2.801	0.504	0.586	0.385	0.300	0.230	0.037
8	88 %	**5.638**	0.451	196.024	15.682	1.005	0.151	0.933	0.168	0.305	0.531	0.300	0.337	0.054
9	52 %	**2.807**	0.225	136.278	10.902	1.214	0.182	0.992	0.179	0.470	0.163	0.300	0.390	0.063
10	50 %	**3.442**	0.275	157.552	12.604	0.832	0.125	0.647	0.116	0.346	0.251	0.300	0.390	0.063
11	80 %	**3.077**	0.246	92.881	7.431	0.259	0.039	0.267	0.048	0.058	0.169	0.300	0.360	0.058
12	57 %	**4.347**	0.348	205.418	16.433	0.601	0.090	0.460	0.083	0.256	0.148	0.300	0.547	0.088
13	49 %	**4.492**	0.359	181.280	14.502	0.625	0.094	1.056	0.190	-0.167	0.168	0.300	0.430	0.069
14	50 %	**4.858**	0.389	167.470	13.398	1.737	0.261	1.579	0.284	0.552	0.613	0.300	0.330	0.053

No.	Load	CO [mg/m³]	Uncer-tainty [mg/m³]	NO_x as NO_2 [mg/m³]	Uncer-tainty [mg/m³]	TOC [mg/m³]	Uncer-tainty [mg/m³]	Methane [mg/m³]	Uncer-tainty [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Uncer-tainty [mg/m³]	Smoke number	Uncer-tainty
15	35 %	**5.929**	0.474	184.059	14.725	1.161	0.174	0.323	0.058	0.919	0.688	0.300	0.517	0.083
16	47 %	**5.756**	0.460	204.634	16.371	1.509	0.226	0.625	0.113	1.040	0.700	0.300	0.527	0.085
17	52 %	**1.909**	0.153	210.659	16.853	1.111	0.167	1.480	0.266	0.001	0.221	0.300	0.057	0.009
18	20 %	**27.140**	2.171	176.590	14.127	0.940	0.141	0.834	0.150	0.314	1.254	0.300	1.507	0.243
19	68 %	**5.804**	0.464	138.607	11.089	0.482	0.072	1.184	0.213	-0.406	0.484	0.300	0.833	0.134
20	80 %	**3.618**	0.289	82.703	6.616	0.898	0.135	1.521	0.274	-0.243	0.288	0.300	0.197	0.032
21	30 %	**31.698**	2.536	140.407	11.233	1.377	0.207	1.836	0.330	0.000	2.500	0.300	0.890	0.143
22	40 %	**9.075**	0.726	183.506	14.680	1.321	0.198	1.881	0.339	-0.090	1.684	0.300	0.400	0.064
23	66 %	**4.459**	0.357	176.808	14.145	1.363	0.204	1.789	0.322	0.021	0.511	0.300	0.133	0.021
24	100 %	**6.382**	0.511	95.845	7.668	0.459	0.069	0.508	0.091	0.078	0.356	0.300	0.243	0.039
25	100 %	**9.780**	0.782	228.978	18.318	0.612	0.092	0.264	0.048	0.413	0.159	0.300	0.087	0.014
26	48 %	**2.473**	0.198	186.534	14.923	0.894	0.134	0.596	0.107	0.447	0.126	0.300	0.113	0.018
27	74 %	**1.839**	0.147	154.120	12.330	0.503	0.075	0.526	0.095	0.108	2.866	0.300	0.440	0.071
28	38 %	**3.701**	0.296	151.598	12.128	1.827	0.274	1.105	0.199	0.999	0.358	0.300	0.280	0.045

Note: Data marked in bold were not included in the calculation of the emission factor. The underlined data refer to new plants.

Source: own measurements

Table 79: Measured values and measurement uncertainties for natural gas plants (average of three consecutive measurements, usually 30 minutes each)

No.	Load	CO [mg/m³]	Uncer-tainty [mg/m³]	NO_x as NO_2 [mg/m³]	Uncer-tainty [mg/m³]	TOC [mg/m³]	Uncer-tainty [mg/m³]	Methane [mg/m³]	Uncer-tainty [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Uncer-tainty [mg/m³]
1	60 %	**0.929**	0.074	179.485	14.359	0.718	0.108	0.843	0.152	0.086	**0.436**	0.300
2	40 %	**0.765**	0.061	63.310	5.065	0.446	0.067	0.796	0.143	-0.151	**0.224**	0.300
3	100 %	**3.611**	0.289	97.308	7.785	0.572	0.086	0.404	0.073	0.269	**0.487**	0.300
4	51 %	**3.207**	0.257	68.487	5.479	0.631	0.095	0.559	0.101	0.212	**0.356**	0.300
5	20 %	**3.084**	0.247	87.704	7.016	2.473	0.371	2.705	0.487	0.444	**0.434**	0.300
6	100 %	**3.721**	0.298	142.987	11.439	1.326	0.199	0.141	0.025	1.220	**2.491**	0.300
7	40 %	**4.296**	0.344	136.768	10.941	0.492	0.074	0.347	0.062	0.232	0.267	0.300
8	35 %	**2.618**	0.209	165.581	13.246	0.785	0.118	0.701	0.126	0.259	0.233	0.300
9	36 %	**2.606**	0.208	163.427	13.074	0.696	0.104	0.503	0.091	0.319	0.264	0.300
10	77 %	**2.691**	0.215	55.563	4.445	0.366	0.055	0.417	0.075	0.054	**0.153**	0.300
11	63 %	**2.986**	0.239	108.247	8.660	0.676	0.101	0.900	0.162	0.001	0.156	0.300
12	65 %	**3.194**	0.256	114.905	9.192	0.754	0.113	1.235	0.222	-0.172	0.160	0.300
13	67 %	**3.131**	0.250	140.968	11.277	0.518	0.078	0.929	0.167	-0.178	**0.098**	0.300
14	23 %	**3.126**	0.250	88.664	7.093	0.623	0.093	0.727	0.131	0.078	**0.160**	0.300
15	20 %	**4.554**	0.364	148.210	11.857	0.869	0.130	2.178	0.392	-0.764	0.151	0.300
16	40 %	**5.436**	0.435	171.043	13.683	0.639	0.096	0.594	0.107	0.194	**0.630**	0.300

No.	Load	CO [mg/m³]	Uncer-tainty [mg/m³]	NO_x as NO_2 [mg/m³]	Uncer-tainty [mg/m³]	TOC [mg/m³]	Uncer-tainty [mg/m³]	Methane [mg/m³]	Uncer-tainty [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Uncer-tainty [mg/m³]
17	28 %	**4.996**	0.400	182.307	14.585	0.737	0.110	0.628	0.113	0.266	**0.525**	0.300
18	75 %	**2.861**	0.229	69.679	5.574	0.250	0.037	0.331	0.060	0.002	0.229	0.300
19	80 %	**2.248**	0.180	96.802	7.744	1.668	0.250	1.477	0.266	0.561	**0.153**	0.300
20	95 %	**1.552**	0.124	105.438	8.435	1.032	0.155	1.444	0.260	-0.051	0.213	0.300
21	95 %	**2.648**	0.212	99.966	7.997	0.943	0.141	0.722	0.130	0.402	**1.843**	0.300
22	40 %	**2.734**	0.219	110.991	8.879	0.693	0.104	0.900	0.162	0.018	0.293	0.300
23	20 %	**3.664**	0.293	136.927	10.954	0.676	0.101	0.827	0.149	0.055	**0.503**	0.300
24	60 %	**4.656**	0.373	103.678	8.294	0.443	0.066	1.329	0.239	-0.553	**0.413**	0.300
25	90 %	**3.000**	0.240	62.693	5.015	0.887	0.133	1.132	0.204	0.038	**0.365**	0.300
26	60 %	**2.703**	0.216	136.263	10.901	1.431	0.215	1.925	0.346	-0.013	**1.919**	0.300
27	50 %	**3.182**	0.255	129.843	10.387	1.135	0.170	1.460	0.263	0.040	**2.520**	0.300
28	87 %	**5.667**	0.453	149.646	11.972	1.500	0.225	1.995	0.359	0.003	**1.219**	0.300
29	93 %	**4.409**	0.353	62.715	5.017	0.528	0.079	0.624	0.112	0.060	**0.248**	0.300
30	100 %	**0.370**	0.030	173.128	13.850	1.917	0.288	1.213	0.218	1.007	0.124	0.300
31	100 %	**0.000**	0.000	117.220	9.378	2.728	0.409	1.292	0.233	1.759	0.117	0.300
32	100 %	**1.409**	0.113	110.324	8.826	2.126	0.319	1.322	0.238	1.134	0.178	0.300
33	100 %	**0.555**	0.044	199.509	15.961	2.367	0.355	1.349	0.243	1.355	0.133	0.300
34	100 %	**0.371**	0.030	103.999	8.320	3.674	0.551	3.487	0.628	1.059	0.116	0.300

No.	Load	CO [mg/m³]	Uncer-tainty [mg/m³]	NO_x as NO_2 [mg/m³]	Uncer-tainty [mg/m³]	TOC [mg/m³]	Uncer-tainty [mg/m³]	Methane [mg/m³]	Uncer-tainty [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Uncer-tainty [mg/m³]
35	100 %	**1.166**	0.093	81.078	6.486	1.874	0.281	1.270	0.229	0.921	0.152	0.300
36	90 %	**0.593**	0.047	118.508	9.481	3.060	0.459	2.837	0.511	0.932	0.129	0.300
37	50 %	**11.316**	0.905	146.831	11.746	3.316	0.497	3.517	0.633	0.678	0.232	0.300
38	65 %	**1239.962**	99.197	**135.380**	10.830	**93.041**	13.956	**97.869**	17.616	19.639	**1.608**	0.300
39	72 %	**1.215**	0.097	219.151	17.532	3.340	0.501	3.135	0.564	0.989	0.163	0.300
40	30 %	**7.088**	0.567	177.092	14.167	4.336	0.650	3.510	0.632	1.704	0.366	0.300
41	90 %	**1.818**	0.145	80.963	6.477	2.409	0.361	2.238	0.403	0.730	0.204	0.300
42	35 %	**2.295**	0.184	120.206	9.616	3.038	0.456	2.614	0.470	1.078	0.234	0.300
43	46 %	**1.439**	0.115	111.969	8.958	2.435	0.365	2.103	0.378	0.858	0.109	0.300
44	72 %	**3.064**	0.245	107.430	8.594	2.133	0.320	1.722	0.310	0.842	0.090	0.300
45	64 %	**4.463**	0.357	101.015	8.081	2.192	0.329	1.616	0.291	0.981	0.109	0.300
46	100 %	**2.807**	0.225	120.118	9.609	0.739	0.111	0.637	0.115	0.262	**0.171**	0.300
47	39 %	**2.587**	0.207	91.748	7.340	1.012	0.152	0.674	0.121	0.507	**0.117**	0.300
48	52 %	**3.223**	0.258	79.951	6.396	1.260	0.189	0.865	0.156	0.611	0.815	0.300
49	74 %	**1.747**	0.140	151.747	12.140	0.413	0.062	0.473	0.085	0.059	**1.262**	0.300
50	93 %	**1.190**	0.095	123.178	9.854	0.750	0.112	0.702	0.126	0.224	0.237	0.300
51	40 %	**1.530**	0.122	72.973	5.838	0.758	0.114	0.676	0.122	0.252	0.089	0.300
52	50 %	**5.408**	0.433	93.441	7.475	1.254	0.188	0.806	0.145	0.649	0.121	0.300

No.	Load	CO $[mg/m^3]$	Uncer-tainty $[mg/m^3]$	NO_x as NO_2 $[mg/m^3]$	Uncer-tainty $[mg/m^3]$	TOC $[mg/m^3]$	Uncer-tainty $[mg/m^3]$	Methane $[mg/m^3]$	Uncer-tainty $[mg/m^3]$	NMVOC (calculated) $[mg/m^3]$	Dust $[mg/m^3]$	Uncer-tainty $[mg/m^3]$
53	50 %	**9.743**	0.779	96.272	7.702	1.418	0.213	1.108	0.199	0.587	0.089	0.300
54	51 %	**13.297**	1.064	87.489	6.999	1.590	0.239	1.142	0.206	0.734	0.119	0.300
55	49 %	**9.046**	0.724	88.881	7.110	1.126	0.169	0.790	0.142	0.533	0.118	0.300
56	12 %	**0.157**	0.013	164.963	13.197	0.516	0.077	0.160	0.029	0.396	0.158	0.300
57	12 %	**0.599**	0.048	151.788	12.143	0.421	0.063	0.268	0.048	0.220	0.229	0.300
58	23 %	**0.666**	0.053	83.682	6.695	0.401	0.060	0.257	0.046	0.208	0.163	0.300
59	42 %	**0.820**	0.066	76.408	6.113	0.637	0.096	0.272	0.049	0.433	0.211	0.300
60	33 %	**2.392**	0.200	72.073	5.903	1.293	0.194	1.002	0.155	0.542	0.103	0.300
61	29 %	**2.496**	0.741	73.791	12.353	1.291	0.145	0.861	0.114	0.646	0.088	0.300
62	23 %	**9.260**	0.021	154.419	5.563	0.968	0.542	0.631	0.564	0.495	0.282	0.300
63	16 %	**0.262**	0.021	69.539	5.563	3.612	0.542	3.133	0.564	1.262	0.275	0.300
64	54 %	**2.368**	0.189	128.332	10.267	1.016	0.152	0.953	0.172	0.301	0.110	0.300
65	52 %	**2.130**	0.170	128.840	10.307	0.926	0.139	1.153	0.208	0.061	0.896	0.300
66	35 %	**2.150**	0.172	122.649	9.812	0.867	0.130	0.752	0.135	0.302	0.129	0.300
67	45 %	**0.343**	0.027	84.594	6.768	2.724	0.409	2.859	0.515	0.580	0.162	0.300
68	85 %	**3.270**	0.262	86.232	6.899	0.354	0.053	0.292	0.052	0.135	0.114	0.300
69	80 %	**3.305**	0.264	80.323	6.426	0.491	0.074	0.240	0.043	0.311	0.118	0.300
70	12 %	**1.064**	0.085	169.857	13.589	0.454	0.068	0.361	0.065	0.183	0.172	0.300

No.	Load	CO [mg/m³]	Uncer-tainty [mg/m³]	NO_x as NO_2 [mg/m³]	Uncer-tainty [mg/m³]	TOC [mg/m³]	Uncer-tainty [mg/m³]	Methane [mg/m³]	Uncer-tainty [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Uncer-tainty [mg/m³]
71	56 %	**2.985**	0.239	107.664	8.613	1.265	0.190	0.888	0.160	0.599	0.172	0.300
72	29 %	**2761.297**	220.904	**145.047**	11.604	**594.065**	89.110	**603.101**	108.558	141.739	0.404	0.300

Note: Data marked in bold were not included in the calculation of the emission factor. The underlined data refer to new plants.

Source: own measurements

E Measurement results (standardised, based on 3 % O_2) as maxima without and with addition of measurement uncertainty

Table 80: Maxima of the three measurements, each generally 30 min. without and with measurement uncertainty (MU) (standardised, 3 % reference oxygen) - fuel oil plants

No.	Average plant load	CO [mg/m³]	CO+MU [mg/m³]	NO_x as NO_2 [mg/m³]	NO_x as NO_2 + MU [mg/m³]	TOC [mg/m³]	TOC + MU [mg/m³]	Methane [mg/m³]	Methane + MU [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Dust + MU [mg/m³]	Smoke number [mg/m³]	Smoke number + MU [mg/m³]
1	69 %	2.118	2.288	218.689	236.184	0.688	0.791	0.840	0.992	0.057	0.716	1.016	0.160	0.182
2	37 %	0.962	1.039	107.450	116.046	0.663	0.762	0.562	0.663	0.241	0.967	1.267	0.490	0.558
3	100 %	5.884	6.354	199.668	215.641	0.300	0.345	0.365	0.431	0.026	1.108	1.408	0.480	0.547
4	67 %	4.410	4.763	84.775	91.557	0.677	0.779	0.563	0.664	0.255	0.890	1.190	0.110	0.125
5	31 %	4.302	4.646	156.943	169.498	0.799	0.919	0.400	0.472	0.499	4.261	4.561	0.260	0.296
6	67 %	4.267	4.609	199.361	215.310	0.879	1.011	1.258	1.484	-0.064	0.095	0.395	0.070	0.080
7	10 %	3.841	4.148	124.248	134.188	2.795	3.214	2.906	3.429	0.615	0.553	0.853	0.230	0.262
8	88 %	6.682	7.217	196.285	211.987	1.411	1.622	1.092	1.289	0.592	1.017	1.317	0.350	0.399
9	52 %	2.903	3.135	136.851	147.799	1.791	2.059	1.347	1.590	0.780	0.168	0.468	0.470	0.535
10	50 %	3.570	3.856	159.575	172.341	0.980	1.127	0.660	0.778	0.486	0.274	0.574	0.450	0.512
11	80 %	3.409	3.682	96.787	104.530	0.468	0.538	0.272	0.321	0.264	0.209	0.509	0.440	0.501
12	57 %	4.548	4.912	206.605	223.134	0.651	0.749	0.704	0.830	0.124	0.179	0.479	0.620	0.706
13	49 %	4.700	5.076	181.673	196.207	0.712	0.819	1.244	1.468	-0.221	0.201	0.501	0.480	0.547

No.	Average plant load	CO [mg/m³]	CO+MU [mg/m³]	NO_x as NO_2 [mg/m³]	NO_x as NO_2 + MU [mg/m³]	TOC [mg/m³]	TOC + MU [mg/m³]	Methane [mg/m³]	Methane + MU [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Dust + MU [mg/m³]	Smoke number [mg/m³]	Smoke number + MU [mg/m³]
14	50 %	5.192	5.607	168.027	181.469	1.847	2.124	1.705	2.012	0.568	0.755	1.055	0.400	0.455
15	35 %	6.840	7.387	198.688	214.583	2.147	2.469	0.336	0.397	1.895	0.774	1.074	0.590	0.672
16	47 %	6.225	6.723	219.553	237.117	1.932	2.222	0.634	0.749	1.456	0.846	1.146	0.560	0.638
17	52 %	2.033	2.196	211.365	228.275	1.167	1.342	1.498	1.768	0.043	0.257	0.557	0.080	0.091
18	20 %	30.611	33.060	177.973	192.211	0.970	1.116	1.111	1.311	0.137	1.549	1.849	1.870	2.129
19	68 %	5.833	6.300	139.730	150.909	0.523	0.602	1.291	1.524	-0.445	0.572	0.872	0.900	1.025
20	80 %	3.687	3.982	84.022	90.743	0.906	1.041	1.544	1.822	-0.252	0.306	0.606	0.240	0.273
21	30 %	31.985	34.544	140.949	152.225	1.395	1.604	1.837	2.167	0.017	2.659	2.959	1.020	1.161
22	40 %	11.735	12.674	223.557	241.442	1.649	1.896	2.447	2.887	-0.186	2.024	2.324	0.820	0.934
23	66 %	4.488	4.847	177.136	191.307	1.420	1.633	1.809	2.134	0.063	0.594	0.894	0.160	0.182
24	100 %	6.439	6.954	95.980	103.659	0.542	0.623	0.543	0.641	0.135	0.369	0.669	0.310	0.353
25	100 %	10.108	10.916	229.603	247.971	0.652	0.750	0.266	0.313	0.453	0.160	0.460	0.100	0.114
26	48 %	2.618	2.827	191.135	206.426	0.948	1.091	0.604	0.713	0.495	0.129	0.429	0.180	0.205
27	74 %	2.169	2.343	157.901	170.533	0.627	0.721	0.669	0.789	0.126	3.071	3.371	0.460	0.524
28	38 %	5.915	6.389	167.783	181.206	2.654	3.052	1.246	1.470	1.719	0.439	0.739	0.350	0.399

Source: own figure: Ökopol

Table 81: Maxima of the three measurements, each generally 30 min. without and with measurement uncertainty (MU) (standardised, 3 % reference oxygen) - natural gas plants

No.	Average plant Load	CO [mg/m³]	CO + MU [mg/m³]	NO_x as NO_2 [mg/m³]	NO_x as NO_2 + MU [mg/m³]	TOC [mg/m³]	TOC + MU [mg/m³]	Methane [mg/m³]	Methane + MU [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Dust + MU [mg/m³]
1	60 %	1.020	1.101	179.750	194.130	0.876	1.007	0.846	0.998	0.241	0.440	0.740
2	40 %	0.812	0.877	64.277	69.419	0.452	0.520	0.898	1.059	-0.221	0.451	0.751
3	100 %	3.640	3.931	97.662	105.475	0.772	0.888	0.474	0.560	0.416	0.488	0.788
4	51 %	3.312	3.577	73.066	78.911	0.852	0.980	1.190	1.405	-0.041	0.583	0.883
5	20 %	3.129	3.379	87.902	94.934	2.851	3.279	2.832	3.341	0.727	1.030	1.330
6	100 %	3.735	4.034	143.590	155.078	1.904	2.190	0.317	0.374	1.667	6.362	6.662
7	40 %	4.410	4.763	137.470	148.468	0.586	0.674	0.377	0.445	0.304	0.278	0.578
8	35 %	2.679	2.894	164.269	177.411	0.737	0.847	0.608	0.718	0.281	0.317	0.617
9	36 %	2.699	2.915	166.185	179.480	0.880	1.012	0.897	1.059	0.207	0.260	0.560
10	77 %	3.085	3.332	56.144	60.636	0.402	0.462	0.603	0.711	-0.050	0.168	0.468
11	63 %	3.024	3.266	109.374	118.124	0.680	0.782	0.907	1.070	-0.001	0.179	0.479
12	65 %	3.281	3.543	115.027	124.229	0.795	0.914	1.315	1.551	-0.191	0.181	0.481
13	67 %	3.142	3.393	141.739	153.078	0.585	0.673	0.999	1.178	-0.164	0.113	0.413
14	23 %	3.200	3.455	89.615	96.784	0.684	0.787	0.832	0.982	0.060	0.177	0.477
15	20 %	4.669	5.042	148.952	160.868	0.712	0.819	2.349	2.772	-1.049	0.178	0.478
16	40 %	5.656	6.108	171.377	185.088	0.652	0.749	0.692	0.816	0.133	0.669	0.969

No.	Average plant Load	CO [mg/m³]	CO + MU [mg/m³]	NO_x as NO_2 [mg/m³]	NO_x as NO_2 + MU [mg/m³]	TOC [mg/m³]	TOC + MU [mg/m³]	Methane [mg/m³]	Methane + MU [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Dust + MU [mg/m³]
17	28 %	5.104	5.513	182.615	197.224	0.758	0.871	0.650	0.767	0.270	0.604	0.904
18	75 %	3.595	3.883	70.373	76.003	0.473	0.544	0.449	0.530	0.137	0.276	0.576
19	80 %	2.570	2.776	97.814	105.639	2.263	2.602	1.534	1.811	1.112	0.194	0.494
20	95 %	1.669	1.803	105.816	114.281	1.087	1.250	1.470	1.735	-0.016	0.248	0.548
21	95 %	3.171	3.424	100.807	108.871	0.999	1.149	0.876	1.034	0.342	4.862	5.162
22	40 %	2.836	3.063	112.779	121.802	0.726	0.834	0.912	1.076	0.041	0.383	0.683
23	20 %	3.714	4.011	137.561	148.566	0.695	0.799	0.869	1.026	0.043	0.551	0.851
24	60 %	4.908	5.301	104.745	113.124	0.443	0.510	1.447	1.707	-0.642	0.582	0.882
25	90 %	3.023	3.265	63.157	68.209	1.002	1.152	1.168	1.378	0.126	0.447	0.747
26	60 %	2.731	2.950	136.844	147.791	1.582	1.820	2.136	2.520	-0.019	1.994	2.294
27	50 %	3.413	3.686	133.965	144.682	1.309	1.505	1.748	2.063	-0.002	4.453	4.753
28	87 %	6.005	6.486	150.027	162.030	1.643	1.890	2.244	2.648	-0.040	2.100	2.400
29	93 %	4.594	4.962	63.000	68.040	0.576	0.663	0.709	0.837	0.044	0.296	0.596
30	100 %	0.560	0.605	177.923	192.157	1.979	2.275	1.275	1.505	1.022	0.132	0.432
31	100 %	0.037	0.040	117.603	127.011	2.779	3.196	1.374	1.622	1.748	0.119	0.419
32	100 %	1.744	1.884	110.980	119.859	2.168	2.493	1.357	1.601	1.150	0.187	0.487
33	100 %	0.903	0.976	217.105	234.473	2.523	2.902	1.457	1.719	1.431	0.153	0.453

No.	Average plant Load	CO [mg/m³]	CO + MU [mg/m³]	NO_x as NO_2 [mg/m³]	NO_x as NO_2 + MU [mg/m³]	TOC [mg/m³]	TOC + MU [mg/m³]	Methane [mg/m³]	Methane + MU [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Dust + MU [mg/m³]
34	100 %	0.585	0.631	105.328	113.755	3.771	4.336	3.636	4.290	1.044	0.118	0.418
35	100 %	1.187	1.282	81.246	87.746	1.959	2.253	1.377	1.625	0.926	0.246	0.546
36	90 %	0.707	0.763	118.713	128.210	3.100	3.565	2.960	3.493	0.880	6.049	6.349
37	50 %	11.607	11.664	148.694	158.191	3.503	3.968	3.717	4.249	0.716	0.238	0.538
38	65 %	1939.434	2094.589	144.008	155.529	106.551	122.534	110.509	130.400	23.670	2.385	2.685
39	72 %	1.357	1.465	222.814	240.639	3.919	4.507	3.737	4.410	1.116	0.199	0.499
40	30 %	7.245	7.825	177.489	191.688	4.739	5.450	3.717	4.386	1.951	0.515	0.815
41	90 %	1.946	2.102	82.552	89.156	2.468	2.838	2.291	2.704	0.749	0.251	0.551
42	35 %	2.508	2.709	125.709	135.766	3.142	3.613	2.734	3.226	1.091	0.284	0.584
43	46 %	1.516	1.637	112.201	121.177	2.444	2.810	2.734	3.226	0.393	0.284	0.584
44	72 %	3.313	3.578	109.858	118.647	2.150	2.472	1.894	2.235	0.729	0.092	0.392
45	64 %	5.044	5.447	102.483	110.682	2.214	2.546	1.657	1.956	0.971	0.112	0.412
46	100 %	2.880	3.111	121.077	130.763	0.797	0.917	0.766	0.904	0.223	0.173	0.473
47	39 %	2.824	3.050	92.138	99.509	1.100	1.266	0.732	0.864	0.552	0.123	0.423
48	52 %	5.007	5.407	81.475	87.992	1.413	1.625	1.184	1.397	0.525	0.895	1.195
49	74 %	1.965	2.123	152.213	164.390	0.417	0.480	0.561	0.662	-0.004	1.446	1.746
50	93 %	1.512	1.633	123.895	133.807	0.805	0.926	0.723	0.853	0.263	0.293	0.593

No .	Average plant Load	CO [mg/m³]	CO + MU [mg/m³]	NO_x as NO_2 [mg/m³]	NO_x as NO_2 + MU [mg/m³]	TOC [mg/m³]	TOC + MU [mg/m³]	Methane [mg/m³]	Methane + MU [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Dust + MU [mg/m³]
51	40 %	1.769	1.911	73.673	79.567	0.819	0.942	0.757	0.893	0.252	0.090	0.390
52	50 %	5.916	6.389	93.823	101.329	1.346	1.548	0.931	1.099	0.648	0.124	0.424
53	50 %	11.087	11.974	96.659	104.391	1.537	1.768	1.190	1.404	0.645	0.108	0.408
54	51 %	14.469	15.626	87.614	94.623	1.698	1.952	1.240	1.464	0.767	0.144	0.444
55	49 %	9.746	10.525	89.058	96.182	1.253	1.441	1.047	1.236	0.468	0.150	0.450
56	12 %	0.213	0.230	165.643	178.894	0.677	0.779	0.193	0.227	0.533	0.193	0.493
57	12 %	0.774	0.836	158.886	171.597	0.432	0.496	0.318	0.376	0.193	0.275	0.575
58	23 %	0.783	0.845	84.025	90.747	0.433	0.498	0.257	0.303	0.240	0.165	0.465
59	42 %	1.109	1.198	76.802	82.946	0.673	0.774	0.276	0.326	0.466	0.292	0.592
60	33 %	2.492	2.695	72.415	78.615	1.316	1.510	1.212	1.374	0.407	0.109	0.409
61	29 %	2.538	4.549	77.491	90.500	1.292	1.477	0.898	1.045	0.618	0.093	0.393
62	23 %	25.133	25.163	162.610	168.264	1.229	1.787	0.816	1.402	0.617	0.669	0.969
63	16 %	0.379	0.410	70.671	76.325	3.726	4.285	3.254	3.840	1.285	0.275	0.575
64	54 %	2.595	2.802	137.188	148.163	1.057	1.215	0.990	1.168	0.314	0.157	0.457
65	52 %	2.208	2.385	130.044	140.448	1.005	1.156	1.181	1.394	0.119	0.918	1.218
66	35 %	2.175	2.349	123.282	133.144	0.886	1.019	0.833	0.983	0.261	0.140	0.440
67	45 %	0.488	0.527	85.587	92.434	2.921	3.359	2.952	3.483	0.707	0.170	0.470

No.	Average plant Load	CO [mg/m³]	CO + MU [mg/m³]	NO_x as NO_2 [mg/m³]	NO_x as NO_2 + MU [mg/m³]	TOC [mg/m³]	TOC + MU [mg/m³]	Methane [mg/m³]	Methane + MU [mg/m³]	NMVOC (calculated) [mg/m³]	Dust [mg/m³]	Dust + MU [mg/m³]
68	85 %	3.289	3.552	86.589	93.516	0.395	0.454	0.335	0.396	0.143	0.124	0.424
69	80 %	3.592	3.880	81.347	87.855	0.665	0.764	0.285	0.336	0.451	0.154	0.454
70	12 %	1.170	1.263	170.517	184.159	0.454	0.523	0.375	0.443	0.173	0.245	0.545
71	56 %	3.798	4.102	145.462	157.099	1.483	1.706	1.326	1.565	0.489	0.222	0.522
72	29 %	3023.670	3265.564	152.456	164.652	777.817	894.490	784.309	925.484	189.586	0.677	0.977

Source: own measurements

F Measured values used in the determination of emission factors

Table 82 shows measurement data without deduction or addition of measurement uncertainty, which were included in the determination of emission factors for existing installations (installed before 20 December 2018). Five measurements were carried out at new installations (No. 57, 60, 61, 67, 68), whose emission values were included in emission factors for new installations.

Table 82: Measured values from own measurements at plants with 1 MW to less than 10 MW that have been included in emission factors

No.	Plant installation	Fuel type of burner	Power output [MW]	Fuel oil [h/a]	Natural gas [h/a]	Fuel oil NOx [mg/Nm³]	Fuel oil TOC [mg/Nm³]	Fuel oil Methane [mg/Nm³]	Fuel oil dust [mg/Nm³]	Natural gas NOx [mg/Nm³]	Natural gas TOC [mg/Nm³]	Natural gas Methane [mg/Nm³]	Natural gas Dust [mg/Nm³]
1	Before 20. 12.2018	Dual fuel	5 - < 10	0	2500	218.14	0.674	0.840	0.635	179.49	0.718	0.843	
2	Before 20. 12.2018	Dual fuel	5 - < 10	3	2	104.42	0.551	0.513	0.601	63.31	0.446	0.796	
3	Before 20. 12.2018	Dual fuel	1 - < 5	20	616	196.40	0.274	0.288	0.709	97.31	0.572	0.404	
4	Before 20. 12.2018	Dual fuel	1 - < 5	400	800	80.89	0.536	0.418	0.505	68.49	0.631	0.559	
5	Before 20. 12.2018	Fuel oil	5 - < 10	10		155.94	0.733	0.338	3.022				
6	Before 20. 12.2018	Fuel oil	1 - < 5	219		198.69	0.842	1.192	0.095				
7	Before 20. 12.2018	Dual fuel	5 - < 10	31	6554	120.46	2.687	2.801	0.385	87.70	2.473	2.705	
8	Before 20. 12.2018	Natural gas	1 - < 5		550					142.99	1.326	0.141	

No.	Plant installation	Fuel type of burner	Power output [MW]	Fuel oil [h/a]	Natu-ral gas [h/a]	Fuel oil NOx [mg/Nm^3]	Fuel oil TOC [mg/Nm^3]	Fuel oil Methane [mg/Nm^3]	Fuel oil dust [mg/Nm^3]	Natural gas NOx [mg/Nm^3]	Natural gas TOC [mg/Nm^3]	Natural gas Methane [mg/Nm^3]	Natural gas Dust [mg/Nm^3]
9	Before 20. 12.2018	Natural gas	1 - < 5		614					136.77	0.492	0.347	0.267
10	Before 20. 12.2018	Fuel oil	1 - < 5	2		196.02	1.005	0.933	0.531				
11	Before 20. 12.2018	Fuel oil	1 - < 5	0		136.28	1.214	0.992	0.163				
12	Before 20. 12.2018	Fuel oil	1 - < 5	105		157.55	0.832	0.647	0.251				
13	Before 20. 12.2018	Natural gas	1 - < 5		2373					165.58	0.785	0.701	0.233
14	Before 20. 12.2018	Natural gas	1 - < 5		3127					163.43	0.696	0.503	0.264
15	Before 20. 12.2018	Dual fuel	1 - < 5	29	1971	92.88	0.259	0.267	0.169	55.56	0.366	0.417	
16	Before 20. 12.2018	Natural gas	1 - < 5		2850					108.25	0.676	0.900	0.156
17	Before 20. 12.2018	Natural gas	1 - < 5		2850					114.91	0.754	1.235	0.160
18	Before 20. 12.2018	Dual fuel	1 - < 5	10	2990	205.42	0.601	0.460	0.148	140.97	0.518	0.929	
19	Before 20. 12.2018	Dual fuel	1 - < 5	2	0	181.28	0.625	1.056	0.168	88.66	0.623	0.727	

No.	Plant installation	Fuel type of burner	Power output [MW]	Fuel oil [h/a]	Natu-ral gas [h/a]	Fuel oil NOx [mg/Nm³]	Fuel oil TOC [mg/Nm³]	Fuel oil Methane [mg/Nm³]	Fuel oil dust [mg/Nm³]	Natural gas NOx [mg/Nm³]	Natural gas TOC [mg/Nm³]	Natural gas Methane [mg/Nm³]	Natural gas Dust [mg/Nm³]
20	Before 20. 12.2018	Natural gas	1 - < 5		553					148.21	0.869	2.178	0.151
21	Before 20. 12.2018	Fuel oil	1 - < 5	100		167.47	1.737	1.579	0.613				
22	Before 20. 12.2018	Dual fuel	1 - < 5	3	3246	184.06	1.161	0.323	0.688	171.04	0.639	0.594	
23	Before 20. 12.2018	Dual fuel	1 - < 5	137	0	204.63	1.509	0.625	0.700	182.31	0.737	0.628	
24	Before 20. 12.2018	Natural gas	1 - < 5		3000					69.68	0.250	0.331	0.229
25	Before 20. 12.2018	Dual fuel	1 - < 5	347	1653	210.66	1.111	1.480	0.221	96.80	1.668	1.477	
26	Before 20. 12.2018	Natural gas	1 - < 5		4000					105.44	1.032	1.444	0.213
27	Before 20. 12.2018	Natural gas	1 - < 5		4000					99.97	0.943	0.722	
28	Before 20. 12.2018	Natural gas	1 - < 5		3000					110.99	0.693	0.900	0.293
29	Before 20. 12.2018	Dual fuel	1 - < 5	3	0	176.59	0.940	0.834	1.254	136.93	0.676	0.827	
30	Before 20. 12.2018	Dual fuel	5 - < 10	0	350	138.61	0.482	1.184	0.484	103.68	0.443	1.329	

No.	Plant installation	Fuel type of burner	Power output [MW]	Fuel oil [h/a]	Natu-ral gas [h/a]	Fuel oil NOx [mg/Nm³]	Fuel oil TOC [mg/Nm³]	Fuel oil Methane [mg/Nm³]	Fuel oil dust [mg/Nm³]	Natural gas NOx [mg/Nm³]	Natural gas TOC [mg/Nm³]	Natural gas Methane [mg/Nm³]	Natural gas Dust [mg/Nm³]
31	Before 20. 12.2018	Dual fuel	1 - < 5	0	3500	82.70	0.898	1.521	0.288	62.69	0.887	1.132	
32	Before 20. 12.2018	Dual fuel	1 - < 5	0	895	140.41	1.377	1.836	2.500	136.26	1.431	1.925	
33	Before 20. 12.2018	Dual fuel	1 - < 5	0	895	183.51	1.321	1.881	1.684	129.84	1.135	1.460	
34	Before 20. 12.2018	Dual fuel	1 - < 5	0	530	176.81	1.363	1.789	0.511	149.65	1.500	1.995	
35	Before 20. 12.2018	Dual fuel	1 - < 5	0	5600	95.85	0.459	0.508	0.356	62.72	0.528	0.624	0.124
36	Before 20. 12.2018	Natural gas	1 - < 5		8000					173.13	1.917	1.213	0.117
37	Before 20. 12.2018	Natural gas	1 - < 5		8000					117.22	2.728	1.292	0.178
38	Before 20. 12.2018	Natural gas	1 - < 5		8000					110.32	2.126	1.322	0.133
39	Before 20. 12.2018	Natural gas	1 - < 5		8000					199.51	2.367	1.349	0.116
40	Before 20. 12.2018	Natural gas	1 - < 5		8000					104.00	3.674	3.487	0.152
41	Before 20. 12.2018	Natural gas	1 - < 5		8000					81.08	1.874	1.270	0.129

No.	Plant installation	Fuel type of burner	Power output [MW]	Fuel oil [h/a]	Natu-ral gas [h/a]	Fuel oil NOx [mg/Nm³]	Fuel oil TOC [mg/Nm³]	Fuel oil Methane [mg/Nm³]	Fuel oil dust [mg/Nm³]	Natural gas NOx [mg/Nm³]	Natural gas TOC [mg/Nm³]	Natural gas Methane [mg/Nm³]	Natural gas Dust [mg/Nm³]
42	Before 20. 12.2018	Natural gas	5 - < 10		5715					118.51	3.060	2.837	0.232
43	Before 20. 12.2018	Natural gas	1 - < 5		3649					146.83	3.316	3.517	0.124
44	Before 20. 12.2018	Natural gas	5 - < 10		8000								
45	Before 20. 12.2018	Natural gas	5 - < 10		8000					219.15	3.340	3.135	0.163
46	Before 20. 12.2018	Natural gas	1 - < 5		130					177.09	4.336	3.510	0.366
47	Before 20. 12.2018	Natural gas	1 - < 5		1000					80.96	2.409	2.238	0.204
48	Before 20. 12.2018	Natural gas	1 - < 5		3987					120.21	3.038	2.614	0.234
49	Before 20. 12.2018	Natural gas	1 - < 5		45					111.97	2.435	2.103	0.109
50	Before 20. 12.2018	Natural gas	1 - < 5		4000					107.43	2.133	1.722	0.090
51	Before 20. 12.2018	Natural gas	1 - < 5		4000					101.01	2.192	1.616	0.109
52	Before 20. 12.2018	Dual fuel	1 - < 5	0	4100	228.98	0.612	0.264	0.159	120.12	0.739	0.637	

No.	Plant installation	Fuel type of burner	Power output [MW]	Fuel oil [h/a]	Natu-ral gas [h/a]	Fuel oil NOx [mg/Nm³]	Fuel oil TOC [mg/Nm³]	Fuel oil Methane [mg/Nm³]	Fuel oil dust [mg/Nm³]	Natural gas NOx [mg/Nm³]	Natural gas TOC [mg/Nm³]	Natural gas Methane [mg/Nm³]	Natural gas Dust [mg/Nm³]
53	Before 20. 12.2018	Dual fuel	1 - < 5	0	4100	186.53	0.894	0.596	0.126	91.75	1.012	0.674	
54	Before 20. 12.2018	Natural gas	1 - < 5		1500					79.95	1.260	0.865	0.815
55	Before 20. 12.2018	Dual fuel	1 - < 5	763	5237	154.12	0.503	0.526	2.866	151.75	0.413	0.473	
56	Before 20. 12.2018	Natural gas	1 - < 5		1800					123.18	0.750	0.702	0.237
57	From 20. 12.2018	Natural gas	1 - < 5										
58	Before 20. 12.2018	Natural gas	1 - < 5		1000					93.44	1.254	0.806	0.121
59	Before 20. 12.2018	Natural gas	1 - < 5		1000					96.27	1.418	1.108	0.089
60	From 20. 12.2018	Natural gas	1 - < 5										
61	From 20. 12.2018	Natural gas	1 - < 5										
62	Before 20. 12.2018	Fuel oil	5 - < 10	720		151.60	1.827	1.105	0.358				
63	Before 20. 12.2018	Natural gas	1 - < 5		4000					164.96	0.516	0.160	0.158

No.	Plant installation	Fuel type of burner	Power output [MW]	Fuel oil [h/a]	Natu-ral gas [h/a]	Fuel oil NOx [mg/Nm³]	Fuel oil TOC [mg/Nm³]	Fuel oil Methane [mg/Nm³]	Fuel oil dust [mg/Nm³]	Natural gas NOx [mg/Nm³]	Natural gas TOC [mg/Nm³]	Natural gas Methane [mg/Nm³]	Natural gas Dust [mg/Nm³]
64	Before 20. 12.2018	Natural gas	1 - < 5		4000					151.79	0.421	0.268	0.229
65	Before 20. 12.2018	Natural gas	1 - < 5		8000					83.68	0.401	0.257	0.163
66	Before 20. 12.2018	Natural gas	1 - < 5		8000					76.41	0.637	0.272	0.211
67	From 20. 12.2018	Natural gas	1 - < 5										
68	From 20. 12.2018	Natural gas	1 - < 5										
69	Before 20. 12.2018	Natural gas	1 - < 5		6000					154.42	0.968	0.631	0.282
70	Before 20. 12.2018	Natural gas	1 - < 5		6300					69.54	3.612	3.133	0.275
71	Before 20. 12.2018	Natural gas	1 - < 5		8130					128.33	1.016	0.953	0.110
72	Before 20. 12.2018	Natural gas	1 - < 5		8250					128.84	0.926	1.153	0.896
73	Before 20. 12.2018	Natural gas	1 - < 5		7900					122.65	0.867	0.752	0.129
74	Before 20. 12.2018	Natural gas	1 - < 5		6680					84.59	2.724	2.859	0.162

No.	Plant installation	Fuel type of burner	Power output [MW]	Fuel oil [h/a]	Natu-ral gas [h/a]	Fuel oil NOx [mg/Nm³]	Fuel oil TOC [mg/Nm³]	Fuel oil Methane [mg/Nm³]	Fuel oil dust [mg/Nm³]	Natural gas NOx [mg/Nm³]	Natural gas TOC [mg/Nm³]	Natural gas Methane [mg/Nm³]	Natural gas Dust [mg/Nm³]
75	Before 20. 12.2018	Natural gas	5 - < 10		7000					86.23	0.354	0.292	0.114
76	Before 20. 12.2018	Natural gas	5 - < 10		7000					80.32	0.491	0.240	0.118
77	Before 20. 12.2018	Natural gas	5 - < 10		100					169.86	0.454	0.361	0.172
78	Before 20. 12.2018	Natural gas	1 - < 5		700					107.66	1.265	0.888	0.172
79	Before 20. 12.2018	Natural gas	1 - < 5		4000					179.49		603.101	0.404

G Comparison of NO_x measured values at different seasons

Table 83 shows NO_x mean values from three measurements, each usually lasting 30 minutes, sorted by the date of measurement and (within the columns for fuel oil and natural gas operation) sorted for each month according to the level of the measured value - with priority given to the natural gas measured values. The measurement uncertainty is not taken into account.

Table 83: NO_x-mean value from three measurements of generally 30 min. duration with month of measurement (without measurement uncertainty) (standardised, 3 % reference oxygen)

Measurement no.	Sector	Month and year of measurement	Fuel oil NO_x as NO_2 [mg/m³]	Natural gas NO_x as NO_2 [mg/m³]
1	Housing	11/2020	218.139	179.485
11	Housing	12/2020	136.278	
5	Housing	12/2020	155.941	
12	Housing	12/2020	157.552	
10	Housing	12/2020	196.024	
6	Housing	12/2020	198.695	
2	Housing	12/2020	104.418	63.310
4	Housing	12/2020	80.892	68.487
7	Housing	12/2020	120.462	87.704
3	Housing	12/2020	196.395	97.308
9	Housing	12/2020		136.768
8	Housing	12/2020		142.987
14	Housing	12/2020		163.427

Measure-ment no.	Sector	Month and year of measurement	Fuel oil NO_x as NO_2 [mg/m³]	Natural gas NO_x as NO_2 [mg/m³]
13	Housing	12/2020		165.581
21	Housing	01/2021	167.470	
15	Housing	01/2021	92.881	55.563
24	Housing	01/2021		69.679
19	Housing	01/2021	181.280	88.664
25	Housing	01/2021	210.659	96.802
27	Housing	01/2021		99.966
30	Housing	01/2021	138.607	103.678
26	Housing	01/2021		105.438
16	Housing	01/2021		108.247
28	Housing	01/2021		110.991
17	Housing	01/2021		114.905
29	Housing	01/2021	176.590	136.927
18	Housing	01/2021	205.418	140.968
20	Housing	01/2021		148.210
22	Housing	01/2021	184.059	171.043
23	Housing	01/2021	204.634	182.307
31	Housing	02/2021	82.703	62.693

Measure-ment no.	Sector	Month and year of measurement	Fuel oil NO_x as NO_2 [mg/m³]	Natural gas NO_x as NO_2 [mg/m³]
35	Housing	02/2021	95.845	62.715
33	Housing	02/2021	183.506	129.843
32	Housing	02/2021	140.407	136.263
34	Housing	02/2021	176.808	149.646
41	Industry	08/2021		81.078
40	Industry	08/2021		103.999
38	Industry	08/2021		110.324
37	Industry	08/2021		117.220
36	Industry	08/2021		173.128
39	Industry	08/2021		199.509
44	Industry	09/2021		135.380
45	Industry	09/2021		219.151
42	Industry	10/2021		118.508
43	Industry	10/2021		146.831
53	Housing	01/2022	186.534	91.748
51	Housing	01/2022		101.015
50	Housing	01/2022		107.430
52	Housing	01/2022	228.978	120.118

Measure-ment no.	Sector	Month and year of measurement	Fuel oil NO_x as NO_2 [mg/m³]	Natural gas NO_x as NO_2 [mg/m³]
62	Industry	02/2022	151.598	
57	Industry	02/2022		72.973
47	Housing	02/2022		80.963
49	Housing	02/2022		111.969
48	Housing	02/2022		120.206
69	Industry	02/2022		154.419
46	Housing	02/2022		177.092
67	Industry	03/2022		72.073
68	Industry	03/2022		73.791
66	Industry	03/2022		76.408
65	Industry	03/2022		83.682
64	Industry	03/2022		151.788
63	Industry	03/2022		164.963
70	Industry	04/2022		69.539
54	Housing	04/2022		79.951
76	Industry	04/2022		80.323
74	Industry	04/2022		84.594
75	Industry	04/2022		86.232

Measure-ment no.	Sector	Month and year of measurement	Fuel oil NO_x as NO_2 [mg/m³]	Natural gas NO_x as NO_2 [mg/m³]
60	Housing	04/2022		87.489
61	Housing	04/2022		88.881
58	Housing	04/2022		93.441
59	Housing	04/2022		96.272
78	Industry	04/2022		107.664
73	Industry	04/2022		122.649
56	Housing	04/2022		123.178
71	Industry	04/2022		128.332
72	Industry	04/2022		128.840
79	Industry	04/2022		145.047
55	Housing	04/2022	154.120	151.747
77	Industry	04/2022		169.857

Source: own measurements

H NO_x - Individual measurement values and associated mean load during measurement

Table 84: Comparison of mean load and NO_x individual measurement values - natural gas (standardised, 3 % reference oxygen content, no measurement uncertainty taken into account)

Measurement no.	Sector	Nominal capacity of the plant [MW]	NO_x as NO_2 [mg/Nm^3] (1st of three measurements)	NO_x as NO_2 [mg/Nm^3] (2nd of three measurements)	NO_x as NO_2 [mg/Nm^3] (3rd of threes measurement)	Mean load as proportion of nominal load] (1st of three measurements)	Mean load as proportion of nominal load] (2nd of threes measurement)	Mean load as proportion of nominal load] (3rd of three measurements)
1	Housing	6.300	179.092	179.614	179.750	62 %	58 %	60 %
2	Housing	9.765	64.277	62.855	62.797	40 %	41 %	39 %
3	Housing	3.045	97.007	97.254	97.662	59 %	59 %	59 %
4	Housing	2.625	73.066	76.866	81.034	42 %	79 %	65 %
5	Housing	6.458	87.902	87.766	87.444	25 %	25 %	25 %
6	Housing	2.442	143.173	142.197	143.590	100 %	100 %	100 %
7	Housing	2.442	135.956	136.877	137.470	40 %	40 %	40 %
8	Housing	4.358	165.138	166.185	165.420	36 %	34 %	34 %
9	Housing	4.358	162.456	163.557	164.269	36 %	36 %	36 %
10	Housing	3.150	56.144	55.324	55.221	90 %	70 %	70 %
11	Housing	1.176	109.374	108.370	106.997	60 %	65 %	65 %
12	Housing	1.176	114.868	115.027	114.821	65 %	65 %	65 %
13	Housing	2.100	141.739	140.663	140.502	60 %	70 %	70 %
14	Housing	3.045	88.919	87.458	89.615	10 %	50 %	10 %

Measurement no.	Sector	Nominal capacity of the plant [MW]	NO_x as NO_2 [mg/Nm³] (1st of three measurements)	NO_x as NO_2 [mg/Nm³] (2nd of three measurements)	NO_x as NO_2 [mg/Nm³] (3rd of threes measurement)	Mean load as proportion of nominal load] (1st of three measurements)	Mean load as proportion of nominal load] (2nd of threes measurement)	Mean load as proportion of nominal load] (3rd of three measurements)
15	Housing	2.442	147.929	148.952	147.750	20 %	20 %	20 %
16	Housing	4.935	171.023	171.377	170.728	40 %	40 %	40 %
17	Housing	4.935	182.615	182.214	182.092	28 %	28 %	28 %
18	Housing	4.200	69.838	68.825	70.373	88 %	75 %	63 %
19	Housing	4.452	95.532	97.058	97.814	80 %	80 %	80 %
20	Housing	2.205	104.838	105.816	105.660	95 %	95 %	95 %
21	Housing	2.205	100.807	99.656	99.436	95 %	95 %	95 %
22	Housing	2.730	110.011	110.184	112.779	40 %	40 %	40 %
23	Housing	4.725	137.561	137.144	136.076	20 %	20 %	20 %
24	Housing	5.145	102.854	103.436	104.745	60 %	60 %	60 %
25	Housing	1.838	63.157	62.616	62.307	90 %	90 %	90 %
26	Housing	1.575	135.621	136.844	136.324	60 %	60 %	60 %
27	Housing	1.575	122.023	133.542	133.965	60 %	60 %	30 %
28	Housing	1.628	149.359	149.552	150.027	60 %	100 %	100 %
29	Housing	1.628	62.398	62.748	63.000	80 %	100 %	100 %
30	Industry	2.100	173.282	168.180	177.923	Normal operation	Normal operation	Normal operation

Measurement no.	Sector	Nominal capacity of the plant [MW]	NO_x as NO_2 [mg/Nm³] (1st of three measurements)	NO_x as NO_2 [mg/Nm³] (2nd of three measurements)	NO_x as NO_2 [mg/Nm³] (3rd of threes measurement)	Mean load as proportion of nominal load] (1st of three measurements)	Mean load as proportion of nominal load] (2nd of threes measurement)	Mean load as proportion of nominal load] (3rd of three measurements)
31	Industry	2.940	116.811	117.603	117.248	Normal operation	Normal operation	Normal operation
32	Industry	1.260	109.551	110.980	110.442	Normal operation	Normal operation	Normal operation
33	Industry	2.100	186.579	217.105	194.843	Normal operation	Normal operation	Normal operation
34	Industry	1.838	102.151	105.328	104.518	Normal operation	Normal operation	Normal operation
35	Industry	1.526	81.057	80.931	81.246	Normal operation	Normal operation	Normal operation
36	Industry	5.229	118.540	118.713	118.272	90 %	90 %	90 %
37	Industry	2.751	148.694	145.916	145.882	50 %	50 %	50 %
38	Industry	8.925	126.251	135.882	144.008	70 %	40 %	85 %
39	Industry	8.925	218.191	222.814	216.448	85 %	50 %	80 %
40	Housing	1.750	176.674	177.114	177.489	26 %	26 %	26 %
41	Housing	1.300	82.552	81.582	78.756	100 %	100 %	100 %
42	Housing	1.750	119.197	125.709	115.712	35 %	35 %	35 %
43	Housing	1.750	112.201	112.017	111.691	35 %	51 %	51 %
44	Housing	1.020	106.832	105.600	109.858	46 %	69 %	69 %

Measurement no.	Sector	Nominal capacity of the plant [MW]	NO_x as NO_2 [mg/Nm³] (1st of three measurements)	NO_x as NO_2 [mg/Nm³] (2nd of three measurements)	NO_x as NO_2 [mg/Nm³] (3rd of threes measurement)	Mean load as proportion of nominal load] (1st of three measurements)	Mean load as proportion of nominal load] (2nd of threes measurement)	Mean load as proportion of nominal load] (3rd of three measurements)
45	Housing	1.020	99.919	102.483	100.642	69 %	64 %	59 %
46	Housing	1.000	121.077	120.004	119.273	100 %	100 %	100 %
47	Housing	3.000	92.138	91.597	91.509	37 %	40 %	40 %
48	Housing	1.800	77.563	80.816	81.475	56 %	56 %	56 %
49	Housing	1.350	152.164	150.864	152.213	74 %	74 %	74 %
50	Housing	3.000	122.754	122.885	123.895	93 %	93 %	93 %
51	Industry	3.500	72.156	73.673	73.091	40 %	40 %	40 %
52	Housing	4.200	93.794	92.705	93.823	60 %	60 %	60 %
53	Housing	4.200	96.025	96.132	96.659	60 %	60 %	60 %
54	Housing	6.800	87.614	87.440	87.414	54 %	54 %	54 %
55	Housing	6.800	88.652	89.058	88.933	49 %	49 %	49 %
56	Industry	2.500	164.642	164.606	165.643	12 %	12 %	12 %
57	Industry	2.500	158.886	148.840	147.638	12 %	12 %	12 %
58	Industry	2.600	84.025	83.670	83.352	23 %	23 %	23 %
59	Industry	2.600	76.802	76.241	76.180	42 %	42 %	42 %
60	Industry	3.200	71.957	71.847	72.415	34 %	34 %	34 %
61	Industry	3.200	71.692	72.189	77.491	22 %	25 %	41 %

Measurement no.	Sector	Nominal capacity of the plant [MW]	NO_x as NO_2 [mg/Nm^3] (1st of three measurements)	NO_x as NO_2 [mg/Nm^3] (2nd of three measurements)	NO_x as NO_2 [mg/Nm^3] (3rd of threes measurement)	Mean load as proportion of nominal load] (1st of three measurements)	Mean load as proportion of nominal load] (2nd of threes measurement)	Mean load as proportion of nominal load] (3rd of three measurements)
62	Industry	3.200	162.610	145.193	155.453	22 %	25 %	22 %
63	Industry	2.000	70.671	69.787	68.160	16 %	16 %	16 %
64	Industry	1.300	137.188	123.712	124.097	38 %	62 %	62 %
65	Industry	3.100	128.109	128.368	130.044	52 %	52 %	52 %
66	Industry	3.100	122.360	123.282	122.304	35 %	35 %	35 %
67	Industry	2.000	85.587	83.829	84.367	45 %	45 %	45 %
68	Industry	6.902	85.813	86.295	86.589	80 %	80 %	94 %
69	Industry	6.902	81.347	79.760	79.863	57 %	90 %	83 %
70	Industry	5.600	169.122	169.932	170.517	25 %	25 %	25 %
71	Industry	4.650	145.462	83.123	94.408	37 %	75 %	56 %
72	Industry	3.200	152.456	144.097	138.589	29 %	29 %	29 %

Source: own measurements

Table 85: Comparison of mean load and NO_x individual measurement values - fuel oil (standardised, 3 % reference oxygen content, no measurement uncertainty taken into account)

Measu-rement no.	Sector	Nominal capacity of the plant [MW]	NO_x as NO_2 [mg/Nm³] (1st of three measurements)	NO_x as NO_2 [mg/Nm³] (2nd of three measurements)	NO_x as NO_2 [mg/Nm³] (3rd of threes measurement)	Mean load as proportion of nominal load] (1st of three measurements)	Mean load as proportion of nominal load] (2nd of threes measurement)	Mean load as proportion of nominal load] (3rd of three measurements)
1	Housing	6.300	218.689	218.329	217.399	72 %	67 %	68 %
2	Housing	9.765	101.663	107.450	104.140	39 %	37 %	34 %
3	Housing	3.045	189.914	199.603	199.668	94 %	94 %	94 %
4	Housing	2.625	84.775	66.244	66.151	56 %	56 %	56 %
5	Housing	9.450	154.308	156.574	156.943	31 %	31 %	31 %
6	Housing	3.875	197.836	198.887	199.361	49 %	49 %	49 %
7	Housing	6.458	116.616	120.522	124.248	13 %	13 %	13 %
8	Housing	1.313	195.723	196.285	196.064	88 %	88 %	88 %
9	Housing	1.470	136.851	136.261	135.723	50 %	50 %	57 %
10	Housing	1.470	159.575	156.525	156.556	57 %	50 %	43 %
11	Housing	3.150	96.787	91.232	90.624	80 %	80 %	80 %
12	Housing	2.100	203.975	206.605	205.675	63 %	57 %	50 %
13	Housing	3.045	180.685	181.673	181.481	49 %	49 %	49 %
14	Housing	1.313	166.943	167.440	168.027	50 %	50 %	50 %
15	Housing	4.935	175.690	198.688	177.799	40 %	40 %	25 %

Measu-rement no.	Sector	Nominal capacity of the plant [MW]	NO_x as NO_2 [mg/Nm³] (1st of three measurements)	NO_x as NO_2 [mg/Nm³] (2nd of three measurements)	NO_x as NO_2 [mg/Nm³] (3rd of threes measurement)	Mean load as proportion of nominal load] (1st of three measurements)	Mean load as proportion of nominal load] (2nd of threes measurement)	Mean load as proportion of nominal load] (3rd of three measurements)
16	Housing	4.935	219.553	196.573	197.776	47 %	47 %	47 %
17	Housing	4.452	209.945	210.667	211.365	70 %	45 %	40 %
18	Housing	4.725	175.227	177.973	176.571	20 %	20 %	20 %
19	Housing	5.145	139.730	138.768	137.323	66 %	66 %	73 %
20	Housing	1.838	80.210	84.022	83.876	80 %	80 %	80 %
21	Housing	1.575	139.832	140.439	140.949	30 %	30 %	30 %
22	Housing	1.575	162.486	223.557	164.473	30 %	60 %	30 %
23	Housing	1.628	176.537	177.136	176.751	66 %	66 %	66 %
24	Housing	1.628	95.980	95.711	95.844	100 %	100 %	100 %
25	Housing	1.000	228.045	229.285	229.603	100 %	100 %	100 %
26	Housing	3.000	185.422	191.135	183.046	47 %	47 %	50 %
27	Housing	1.350	157.901	151.747	152.714	74 %	74 %	74 %
28	Industry	5.500	167.783	149.383	137.628	62 %	31 %	20 %

Source: own measurements

I Plants with less than 300 operating hours per year

Table 86 shows installations for which the operators reported less than 300 operating hours per year. Section 11 (8) of the 44th BImSchV (2019) allows a higher NO_x limit value of 250 mg/Nm³ for installations with 10 MW to less than 20 MW if operated with light fuel oil and if they are in operation for a maximum of 300 hours per year on a moving average over a period of five years.

The measured fuel oil plants do not fall under this regulation as they have a rated thermal input of less than 10 MW. The plants measured exceed the limit value of 200 mg/Nm³ NOx in three out of ten cases (marked in bold).

The 44th BImSchV (2019) does not set a higher limit value for natural gas plants with 10 MW to less than 20 MW if they operate less than 300 hours per year. The limit value applicable to the measured natural gas plants with less than 10 MW is 150 mg/Nm³. In the seven measurements of natural gas plants operating less than 300 hours per year, this limit was exceeded three times (marked in bold).

Table 86: Plants with < 300 operating hours per year and NO_x measured values plus measurement uncertainty (MU) (standardised, based on 3 % oxygen content)

No.	Sector	Dual-fuel burner	Fuel oil and natural gas - annual operating hours	Fuel oil - annual operating hours	Natural gas - annual operating hours	Fuel oil - NO_x as NO_2 + MU [mg/m³]	Natural gas - NO_x as NO_2 + MU [mg/m³]
1	Housing	Yes	5	3	2	112.77	68.374
2	Housing	No	10	10		168.42	
3	Housing	No	219	219		**214.59**	
4	Housing	No	2	2		**211.71**	
5	Housing	No	0	0		147.18	
6	Housing	No	105	105		170.16	
7	Housing	Yes	2	2	0	195.78	95.76
8	Housing	No	100	100		180.87	
9	Housing	Yes	137	137	0	**221.00**	**196.89**

No.	Sector	Dual-fuel burner	Fuel oil and natural gas - annual operating hours	Fuel oil - annual operating hours	Natural gas - annual operating hours	Fuel oil - NO_x as NO_2 + MU [mg/m³]	Natural gas - NO_x as NO_2 + MU [mg/m³]
10	Housing	Yes	3	3	0	190.72	147.88
11	Housing	No	130		130		**191.26**
12	Housing	No	45		45		120.93
13	Industry	No	100		100		**183.45**

Source: own measurements

J Manufacturer information on achievable NO_x emissions depending on the combustion technique

Table 87 was drawn up in an ad-hoc working group under the leadership of the BDH and with the collaboration of the burner manufacturers Dreizler, Elco and Weishaupt.

All NO_x values are given in mg/m^3 at an oxygen reference value of 3 % in dry waste gas.

A range of values within a cell results from possible design differences between the various applications (e.g. combustion chamber diameter, medium temperature, preheating temperature).

As the EU Directive for medium combustion plants (EU Directive 2015) and the corresponding ordinance in Germany (44th BImSchV) do not define any requirements for boundary conditions, the following parameters are defined as specific boundary conditions for this table:

- Combustion air temperature 10 - 40 °C; combustion air humidity 5 - 15 g/kg
- Calorific value of natural gas H (local Wobbe index fluctuation < ±2 % and max. 10 % H_2); nitrogen content in EL fuel oil max. 140 mg/kg
- Provision of measurement uncertainty and additional addition of measurement uncertainties: 10 mg/m^3

The values given thus represent the maximum of the real values over the course of the year. Due to more favourable boundary conditions, lower emissions can also occur and be measured in random samples.

Data for liquid gas (propane/butane) are not listed in the table. According to the burner manufacturers, the emission values for LPG are approx. 1.5-1.8 times higher than for natural gas H (depending on the composition).

Higher hydrogen contents than 10 % in natural gas H have an influence on NO_x emissions, and also on the basic applicability of the low-NO_x techniques listed. This fundamental fact is not taken into account in the table.

All values result from a large number of measurement protocols from different manufacturers on the various applications under different conditions with regard to the influencing factors.

Table 87: Achievable NO_x emissions by burner technique and boiler design in medium combustion plants for fuel oil and natural gas

No.	Boiler design Technique	Shell boilers based on the through-firing principle [mg/m³]	Shell boilers using the reverse flame principle [mg/m³]	Thermal oil boiler with air preheating up to 200°C [mg/m³]	Air heater (indirect) using the burn-through principle [mg/m³]	Air heater (indirect) in reverse principle [mg/m³]
1	Standard burner (not Low-NOx) + external flue gas recirculation (0th generation)	unusual because low-NOx technique is available	Fuel oil 200 - 250 Natural gas 100 - 120	unusual because low-NOx technique is available	unusual because low-NOx technique is available	Fuel oil 200 - 250 Natural gas 100 - 120
2	Internal flue gas recirculation (1st generation)	Fuel oil approx. 250 Natural gas 90 - 150	Fuel oil approx. 250 Natural gas 100 - 150	Fuel oil 250 - 350 Natural gas 150 - 200	Fuel oil approx. 250 Natural gas 90 - 150	Fuel oil approx. 250 Natural gas 100 - 150
3	Internal flue gas recirculation (2nd generation)	Fuel oil 130 - 200 Natural gas 75 - 100	Fuel oil 180 - 250 Natural gas 100 - 120	Fuel oil 180 - 250 Natural gas 100 - 140	Fuel oil 130 - 200 Natural gas 75 - 100	Fuel oil 180 - 250 Natural gas 100 - 120
4	Internal + external flue gas recirculation	Fuel oil 100 - 150 Natural gas 40 - 80	n. a.	Fuel oil 150 - 200 Natural gas 70 - 120	Fuel oil 120 - 150 Natural gas 60 - 80	n. a.
5	Surfaces / Pre-mix burner (up to approx. 4 MW, only gaseous fuels, note cross-media effects)	Fuel oil n. a. Natural gas 30 - 50	Fuel oil n. a. Natural gas 30 - 50	Fuel oil n. a. Natural gas 30 - 50	Fuel oil n. a. Natural gas 30 - 50	Fuel oil n. a. Natural gas 30 - 50
6	SCR / SNCR	Not considered, as secondary reduction technique	Not considered, as secondary reduction technique	Not considered, as secondary reduction technique	Not considered, as secondary reduction technique	Not considered, as secondary reduction technique

Notes on cross-media effects:
1) Energy and efficiency: In general, the lower the NO_x value, the more energy input is required. Either through actual additional energy generated (primary energy), through additional energy losses or additional electrical energy. The following technical causes associated with the above-mentioned low-NO_x techniques should be mentioned: Higher pressure loss at the combustion head, e.g. for internal flue gas recirculation, leads to higher blower output and therefore more electrical energy requirement for the same combustion capacity. External flue gas recirculation leads to additional fan power and therefore more electrical energy requirement for the same combustion capacity. Increased excess air for flame cooling leads to higher flue gas losses (mainly used with surface / pre-mix burners). A quantification, differentiated

according to technique and application and different output ranges and different focal points of the manufacturers, is not possible without further ado, therefore the qualitative and general statement on the connection.
2) Manufacturing costs and price: The lower the NO_x value, the higher the cost. The additional expense results from:
- higher design effort on the burner
- higher expenditure on the design of the application (e.g. larger combustion chamber diameters)
- Exclusion of low-cost applications (e.g. reverse furnaces)
- Higher expenditure in the periphery (e.g. pipe for external exhaust gas recirculation)
- higher costs for control and regulation technique
- higher costs for commissioning and maintenance

Source: BDH for UBA workshop 2022