Emission factors for gas fired CHP units < 25 MW

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ABSTRACT

An emission mapping study has been performed in Denmark on combined heat and power production (CHP) on plants with less than 25 MW electricity power capacity. The paper presents emission factors for gas engines and gas turbines in field operation. The emission factors are based on approximately 500 field measurements on engines and turbines operated on natural gas or biogas.

The species considered in this study includes NO_x, CO CH_4, NMVOC, aldehydes and odour. A screening study was included in order to evaluate emissions of less well documented species. The screening includes N_2O, lubrication oil, particulate matter (PM_1, $PM_{2.5}$ and PM_{10}), butadiene and Polycyclic-Aromatic-Hydrocarbons (PAH).

Validated emission factors were calculated both on specific engine makes and aggregated for gas engines and turbines. The emission factors of NO_x, CO, UHC, aldehydes and odour are well established due to a large number of measurements.

Emission of unburned hydro carbon (UHC) contributes to the global warming potential from gas engines. Compared to complete combustion, the global warming potential for gas engines was on average raised by 20% by the emission of unburned fuel.

A screening study revealed high emissions of lubrication oil emissions from gas engines. It was also documented that emissions during start and stop can contribute significantly to the annual emission from the engine plants. The contribution may pose a problem for engines operated in a liberalised power market with many starts and stops as the power price varies.

INTRODUCTION

Combined heat and power is an important part of the Danish energy infrastructure. Approximately 1/3 of the natural gas used in Denmark is consumed on decentralised CHP plants. The decentralised power produced totals approximately 14% of the total power production in Denmark. As part of a larger emission factor mapping study considering all decentralised production based on natural gas, biogas, waste and biofuels, the Danish Gas Technology Centre has performed an emission factor mapping study on gas fired plants. This includes natural gas fired engines, biogas fired engines and gas turbines running on natural gas.

The emission mapping focused on two targets. The first target was to estimate validated emission factors for all emissions known to originate from gas based CHP production on gas engines and turbines. The emissions considered here were NO_x, CO, UHC (methane + NMVOC), aldehydes and odour. The plant size considered was all plants of less than 25 MW electrical. Due to regulations larger plants must have continuous emission measurements and hence emission data is available for these plants. The existing emission data was validated by comparison with new measurements for the same plants. The second target was to screen the CHP plants for other possible emissions to see if other species than the usual exhaust components might be a problem. The screening study included particulate matter (total suspended particulate (TSP), PM_{10}, $PM_{2.5}$ and PM_1) N_2O, PAH, lubrication oil from engines, and 1.3-butadien. Furthermore, the screening study included emissions during start and stop procedures for gas engines

METHOD

Old Emission Data and Energy Data Collection

A complete list of all CHP plants connected to the public grid was available from the Danish Energy Authority. The list included both CHP plants for public heating as well as industrial CHP plants. All plant owners were contacted in order to ask for whatever information they might have on emissions from their plant. All information was given to the project by the plant owners on the condition that emission data from a single plant should not be recognisable in any published material. Companies performing emission measurements were also contacted and asked for emission data on similar premises. A total of 522 useable emission data sets were collected. The major part of the data sets included data on NO_x, CO and UHC, but also a significant amount of data was colleted on aldehydes (40 sets) and odour emissions from gas engines (100 sets). The data was split in 38 sets from gas turbine sites, 470 sets from engines fuelled by natural gas and 14 sets from biogas engines. The majority of the data sets was from the period 1999 to 2001.

All the emission data was placed in a database and coupled to the Danish Energy Authority's data on fuel consumption for the year 2000. This database was then extended with the DGC knowledge on which make and model of machinery is placed on all sites. The questionnaire to the plant owners included questions on exhaust gas cleaning equipment, and where available, this information was included in the database.

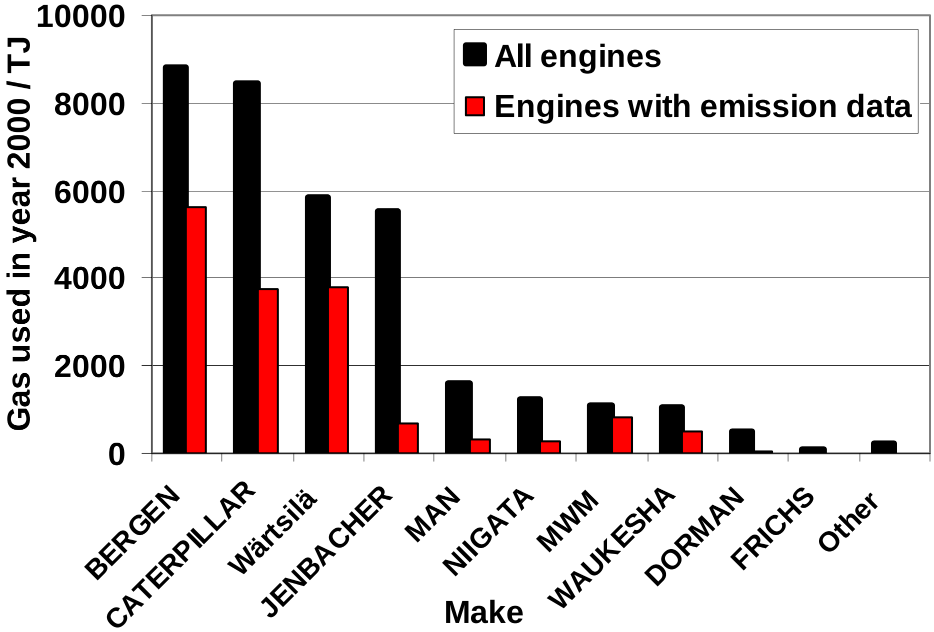

Figure 1 Use of natural gas on gas engine makes for all engines and for engines with old emission data

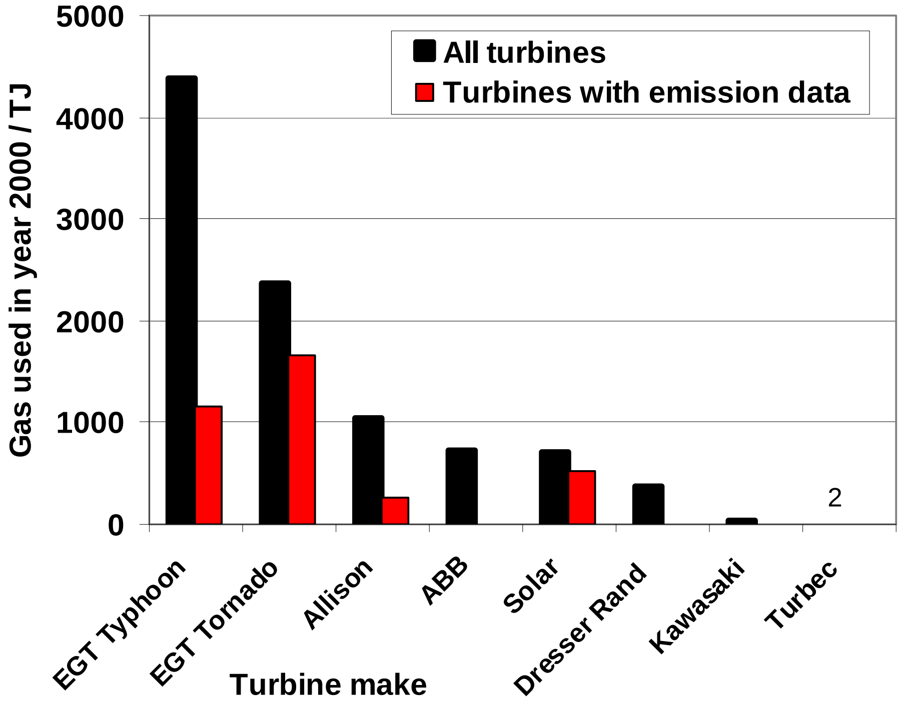

Figure 2 Use of natural gas on gas turbine makes for all turbines and for turbines with old emission data

Collection of New Emission Data

The collected emission data sets were analysed, considering the distribution among the machinery makes and models. A total of 27 new emission measurements were performed during this project. The dual aim of these measurements was to validate the existing emission measurements and to cover makes and models with too few measurements. The decision on where to make new measurements was based on the energy consumption of the different makes and types of engines. Figures 1 and 2 show the distribution of fuel consumption for gas engines and turbines fuelled by natural gas on different makes. The figures also show the amount of engine and turbine energy consumption, on which emission data was available. As can be realised from the figures, new measurements were needed for Jenbacher and MAN gas engines and for ABB and EGT Typhoon gas turbines. The validity tests were performed by preferably selecting plants where emissions measurements had been performed previously. This would make it possible to compare the trend in emissions during some years. The 27 new emission measurements were distributed with 14 on natural gas engines, 6 on gas turbines and 7 on biogas engines. The reader is referred to /1/ for specific information on the measuring program.

Only very few data was available for the screening components before the project. The screening measurements were selected in order to have data on as large a fraction of the makes as possible. In practice, this means that measurements were performed for the major makes of engines and gas turbines installed in Denmark.

Calculation of Emission Factors

In the cases where sufficient data was available, emission factors were calculated as make and model specific emission factors. The make and model specific factors were calculated on an energy consumption average basis. These factors were then aggregated to emission factors for the plant type by weighting the model specific factors by the energy consumption of the plant type. In cases where fewer emission data was available, only aggregated emission factors based on all plants were calculated, again on an energy consumption average basis.

RESULTS

Gas Turbines

NO_x is the only major emission coming from the gas turbines operating on natural gas. Figure 3 gives an overview on the available NO_x emission data for the different makes of gas turbines. All figures and tables are based on dry exhaust gas. As can be seen from the figure, the new data collected is in agreement with the old data. This is further confirmed in Figure 4 where data from three gas turbines is shown for the period from 1998 to 2002. The data from year 2002 is collected in this study and shows an excellent agreement with the old emission data. It was concluded that the old NO_x emission data from the turbine would be usable for the emission factor calculus. Figure 3 shows that large differences are present for the emission of NO_x, even for the same make. EGT Tornado has significantly higher emissions than does the EGT Typhoon. One must remember that the results shown here are for the field engines. Manufacturers have improved their models during the years, and lower emission machines are available for almost all models.

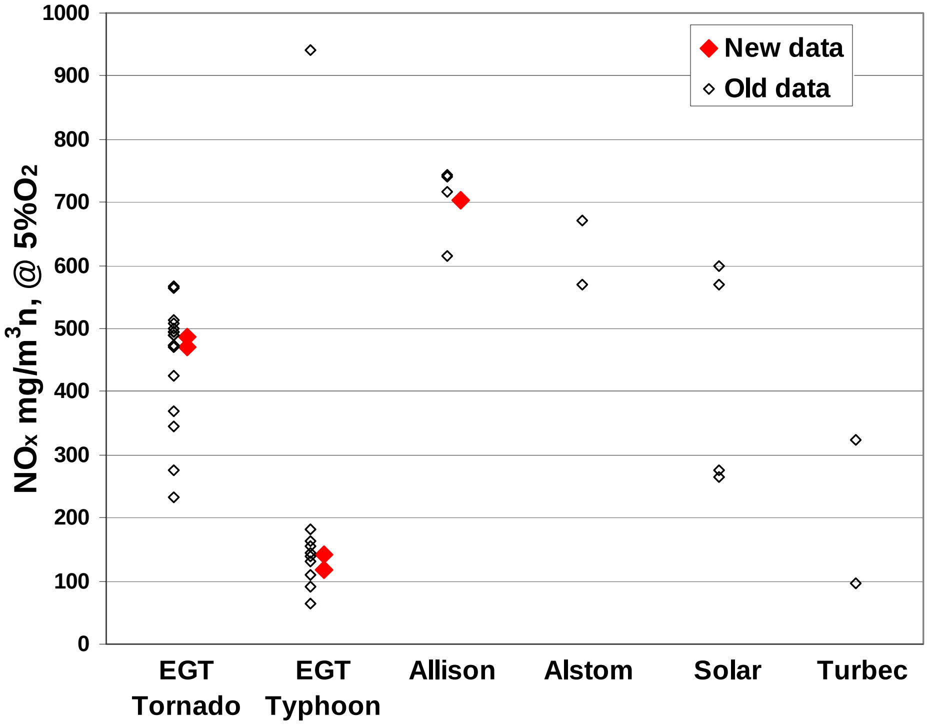

Figure 3   New and old NO_x emission data for natural gas turbines

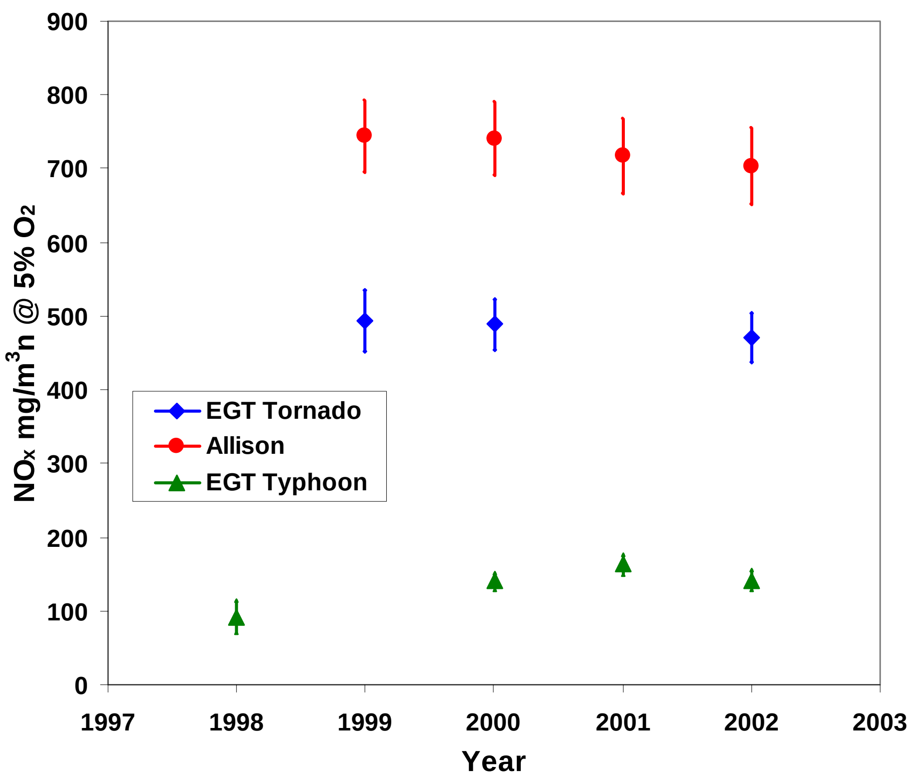

Figure 4   Time series of NO_x emission data for natural gas turbines. Vertical lines show the uncertainty of the NO_x measurements.

The Appendix A table summarises the emission factors found for natural gas turbines in Denmark for all the measured species where emissions were above the sample detection limits. When emissions levels were below the detection limit, the maximum values are shown in the table.

As expected NO_x was the only important emission from the gas turbines. Low emission levels were detected for CO, N_2O odour and particulates. Further analysis of the particulate matter showed that the particles were not combustion related. They are expected to be corrosion products from the heat exchangers on the turbine sites. Emissions of UHC, PAH and aldehydes were very low.

On an energy consumption average basis the Danish gas turbines with a power rating below 25 MW electrical have efficiency for power production of 28.8%. The fuel consumption was a little above 9000 TJ in year 2000. Emission data was available for 6200 TJ or 67% of these for NO_x, and CO. The remaining species were measured on fewer plants.

Natural Gas Fuelled Engines

Typical emission data for gas engines fired with natural gas is shown in Figure 5-7 for NO_x, CO and UHC, respectively, for a few of the makes operating in Denmark. As can be realised from the figures, a substantial amount of data has been collected.

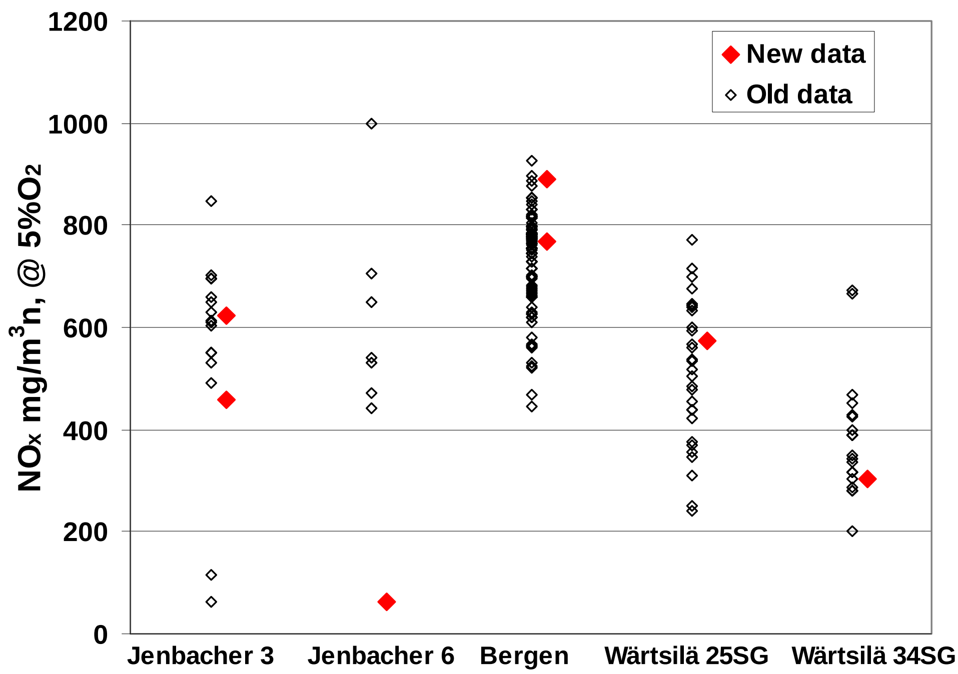

Figure 5 NO_x emission data for natural gas engine makes

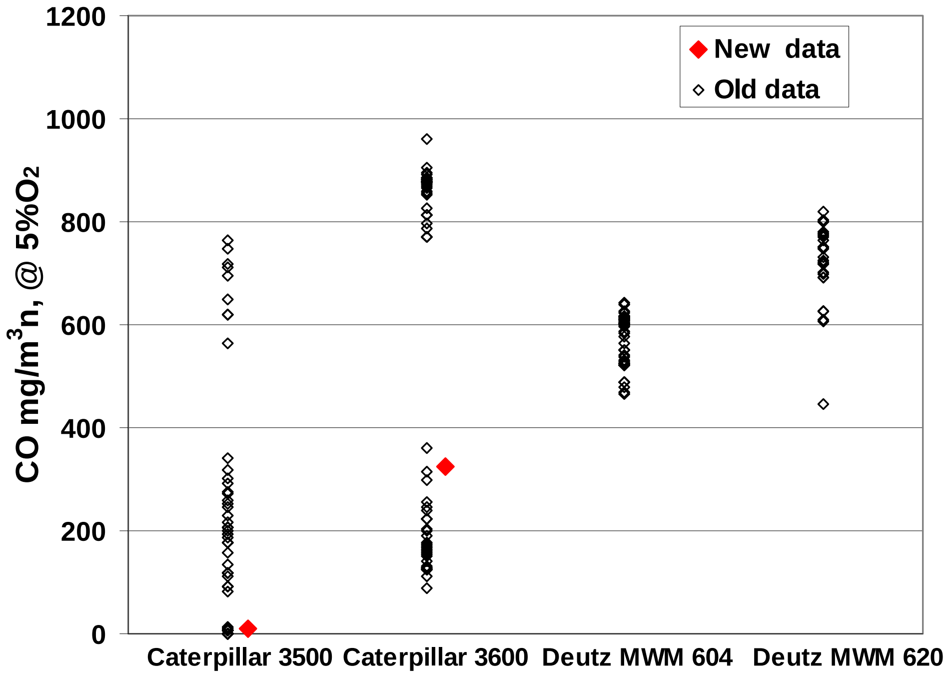

Figure 6 CO emission data for natural gas engine makes

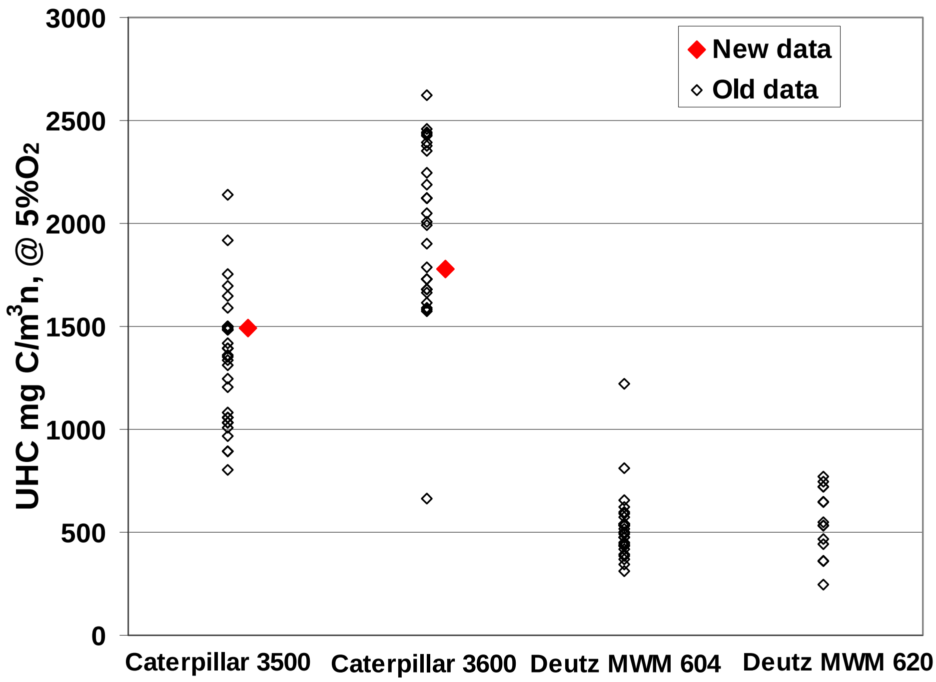

Figure 7 UHC emission data for natural gas engine makes

NO_x emissions vary significantly among the different makes and models and within the individual models. Figure 5 shows this for some of the important models used in Denmark. Even though there is a large variation for NO_x emissions for engines within the individual models, it appears that the individual engine does have stable NO_x emissions over time, as long as the engine is not renovated or emission reduction equipment is not installed. In Figures 8 and 9 this is illustrated by the time series for two Bergen engines and a Caterpillar engine. The current NO_x emission regulation is 650 mg/m^{3}n @ 5% O_2, dry exhaust gas at 30% efficiency. Almost all engines in the study were within this limit.

Figure 6 shows typical CO emissions. For some engine makes we observe a split in two CO emission levels for the same engine model. This is seen in Figure 6 for the two Caterpillar models. The split is due to the fact that some of the engines are equipped with CO catalyst. Some engines have been supplied with CO catalyst from the commissioning, and the remaining part is preparing for new and stricter emission regulation from 2006.

UHC (Unburned Hydro-Carbon) emissions have attracted a large amount of attention in Denmark since large emissions were discovered in 1996. This is the reason for all the old data in Figure 7. Before 1996 only few were doing UHC emission measurements, and after 1996 almost everybody has included these measurements. In 1998 new regulation for UHC was adopted. New engines installed after 1998 must be below 1500 mg C/m^{3}n @ 5% O_2, dry exhaust gas at 30% efficiency. Engines already installed have an exemption for the regulation until year 2006, after which date all engine must be within the regulation. As seen from Figure 7 many engines are outside the allowable emission range and at the time of writing a large effort is done by engine suppliers and plant owners to prepare the engines for the year 2006 limitations. The new collected emission data for UHC was in agreement with the old data.

The emission of UHC was analysed on a gas chromatograph to specify the amount of different hydrocarbon species. The relative composition of the unburned fraction was almost as the relative distribution in the natural gas with two exceptions. The engine exhaust contained unsaturated species ethene and propene (2 and 0.4% of carbon, respectively). These species are not present in the natural gas, but a product of the non-complete combustion process. Furthermore, the exhaust gas contains a relatively smaller amount of higher hydrocarbons (C_2-C_6) than does the natural gas. This probably is a result of the easier oxidation of higher hydrocarbons compared to methane. The detailed analysis results are available for the reader in /1/.

The emission of UHC is in the range of 1-6% of the fuel used on the engines. The energy averaged loss of fuel is approximately 3.6%. This is a significant loss of energy. Even worse, the main component of the UHC is methane (80% of carbon), which is a potential hazard in terms of global warming potential. If we use the IPCC (International Panel on Climate Change) factor of 23 (100 year time horizon) for methane compared to CO_2 on a weight/weight basis, the global warming potential of using natural gas engines in Denmark is 21% above the global warming potential expected at complete combustion. This is a very significant difference. Engine manufacturers have already addressed the problem, and major suppliers are now able to supply new engines with lower UHC emissions.

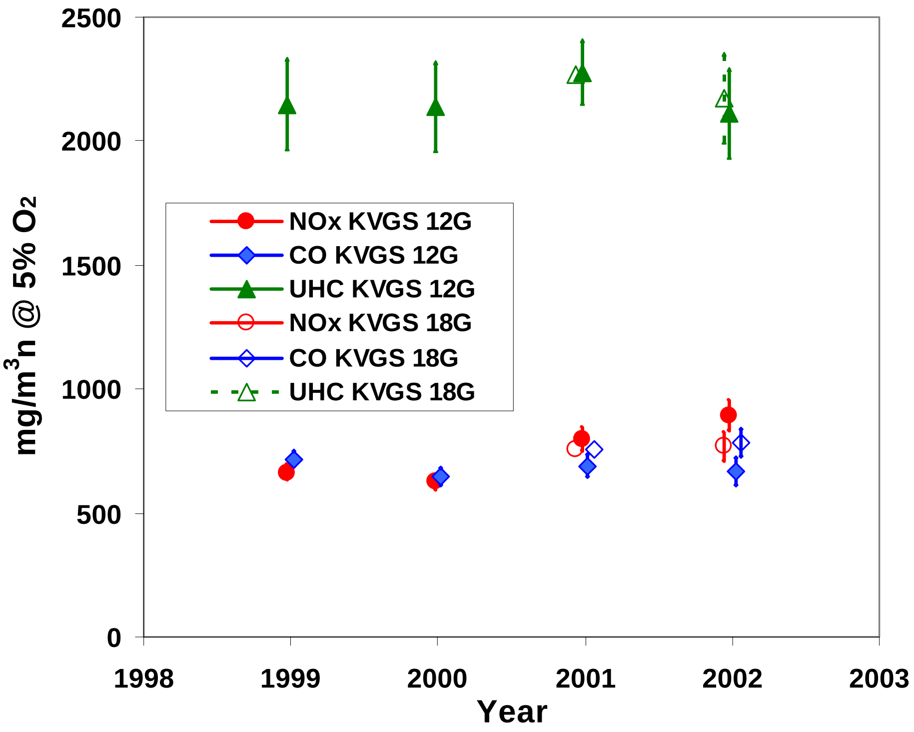

Figure 8 Emission time series for two Bergen natural gas engines

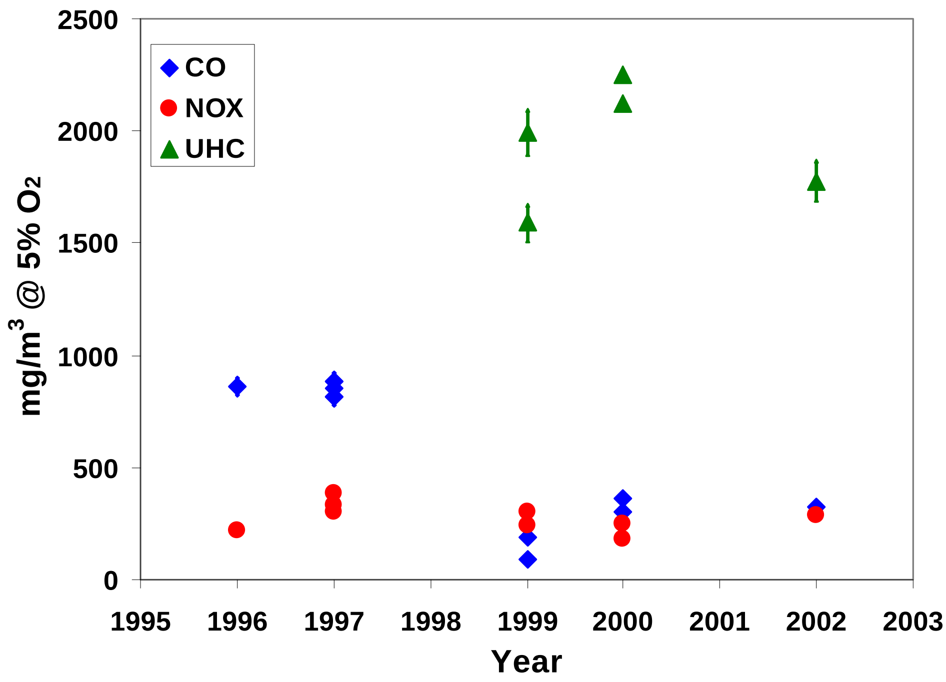

Figure 9 Emission time series for a Caterpillar 3600 natural gas engine. CO catalyst was installed in 1998

Table 1 Make and model specific emissions factors for major types of engines

Engine Make and type	Ber-gen	Cater pillar 3500	Cater pillar 3600	Jenbacher 300	Jenbacher 600	MAN	MAN /B&W	MWM 604	Niigata 26	Wau-kesha	Wärtsilä 25	Wärtsilä 34	Wärtsilä 28	Wärtsilä known type
Ignition type Pre-chamber or Open chamber	Pre-	Pre-	Open	Open	Pre-	Open	Pre-	Open	Pre-	Open	Pre-	Pre-	Pre-	Pre-
Efficiency [%]	39.4	36.3	39.2	38.4	38.8	33.1	38.0	35.1	38.0	33.3	37.2	41.2	41.1	40.2
NO_x [g/GJ]	232	137	91	169	169	125	142	169	93	74	157	121	130	200
UHC (C) [g/GJ]	648	434	611	235	516	74	781	161	891	608	479	413	473	92
CH_4 [g/GJ]	694	465	655	251	553	79	837	173	955	651	514	442	507	98
NMVOC [g/GJ]	156	104	147	56	124	18	188	39	214	146	115	99	114	22
CO [g/GJ]	225	110	145	129	222	165	80	177	122	216	248	163	265	135
Odour (actual exhaust) [OU/m^3]	13996	2241	5338	8679	500	5095	400	10253	2945	4600	10083	8028	11702	3500
Aldehyde														
- Formaldehyde [mg/GJ]	35.22	10.93	24.85	18.67	0.72		0.22	19.86	25.35	32.80	18.55	37.22		1.68
- Acetaldehyde [mg/GJ]	3.05	0.63	2.15	1.08	0.00		0.00	1.57	2.99	1.68	1.53	2.28		0.09
- Acrolein [mg/GJ]	0.15	0.05	0.04	0.14	0.00		0.00	0.03	0.03	0.16	0.06	0.03		0.00
- Propanal [mg/GJ]	0.31	0.04	0.18	0.10	0.00		0.00	0.13	0.22	0.12	0.16	0.17		0.00
- Acetone [mg/GJ]	0.32	0.08	0.28	0.14	0.00		0.00	0.38	0.37	0.06	0.19	0.37		0.00
- Butanal [mg/GJ]	0.15	0.03	0.06	0.05	0.00		0.00	0.05	0.31	0.16	0.06	0.17		0.00
- Pentanal [mg/GJ]	0.15	0.08	0.29	0.04	0.00		0.00	0.35	0.00	0.00	0.00	0.30		0.00
- Hexanal [mg/GJ]	0.02	0.00	0.07	0.00	0.00		0.00	0.02	0.00	0.00	0.00	0.01		0.00
- Benzaldehyd [mg/GJ]	0.04	0.02	0.00	0.03	0.00		0.00	0.04	0.06	0.00	0.00	0.06		0.03
Annual natural gas consumption [TJ]	8841	4185	4287	5124	550	834	614	662	1115	838	838	2130	809	490

The new emission data in general shows good agreement with the existing data in Figures 5-7. In Figures 8 and 9 time series for NO_x CO and UHC for three engines are shown, which confirm the agreement. Wherever possible to show time series in the collected emission data, the time series showed a similar behaviour. The emission level from an engine remained stable during time, unless it was renovated or emission reduction equipment was introduced. Figure 9 shows this clearly for a Caterpillar engine. In 1998 a CO catalyst was installed, causing CO emissions to decrease significantly. The major uncertainty by using the old emission data for calculation of emission factors is in the accuracy of the knowledge on these changes on the plants. In this study a questionnaire to the plant owners gave precise information on the condition of the plants at the time of the study. It must, however, be expected that the emission factors will change during time both as new and lower emission engines are commissioned and when new emission reduction catalysts are installed.

With the amount of data available for gas engines it was possible to derive make and model specific emission factors for the major emission components. These are shown in Table 1. The table in Appendix A gives the aggregated emission factors for all natural gas engines in Denmark.

As can be seen in Table 1, large differences exists in the make and model specific emission factors. This first of all points to the important fact that we should use make and model specific emission factors whenever it is possible in order to obtain the highest possible accuracy of the aggregated emissions and emission factors. We must also remember that the data is a mirror of the field engines in Denmark. Thus the difference among the different makes and models for example in efficiency cannot be taken as proof of the differences among the current technologies. If you are planning to buy an engine you have to compare new performance data. Engine manufacturers continuously improve their engines and the differences observed in this study is more a time picture of the period where the Danish engines were installed and commissioned. The majority of the engines is from the period 1992 to 1998.

Table 1 also contains make and model specific emission factors for odour and different aldehydes. Emission factors for odour vary a lot, even when the analysis uncertainty factor of 2 of the odour panel is considered. In the late 1990's some plants had problems with neighbour complaints about odour emissions. These problems were almost always caused by insufficient chimney heights. The emission of aldehydes from the gas engines is very large. New regulation has been put forward with emission limits for formaldehyde of 10 mg/m^3 @ 5% O_2, dry exhaust and 30% efficiency for new engines. As can be seen from Figure 10 this limit cannot be met by the existing engines. Nor are the manufacturers able to supply an engine with that low formaldehyde emissions. The pre-chamber engines have higher formaldehyde emissions than the open chamber engines, but the spread is rather large for both types. Figure 10 shows two types of exhaust gas treatments, which are able to meet the formaldehyde limits. One is an incineration plant described in /2/. The other type of exhaust gas cleaning, which is able to meet the limits, is the exhaust gas cleaning system used at greenhouses where utilising exhaust gas for CO_2 fertilization. The exhaust gas is treated with both selective catalytic reduction of NO_x using urea or ammonia combined with a very vigorous CO oxidation

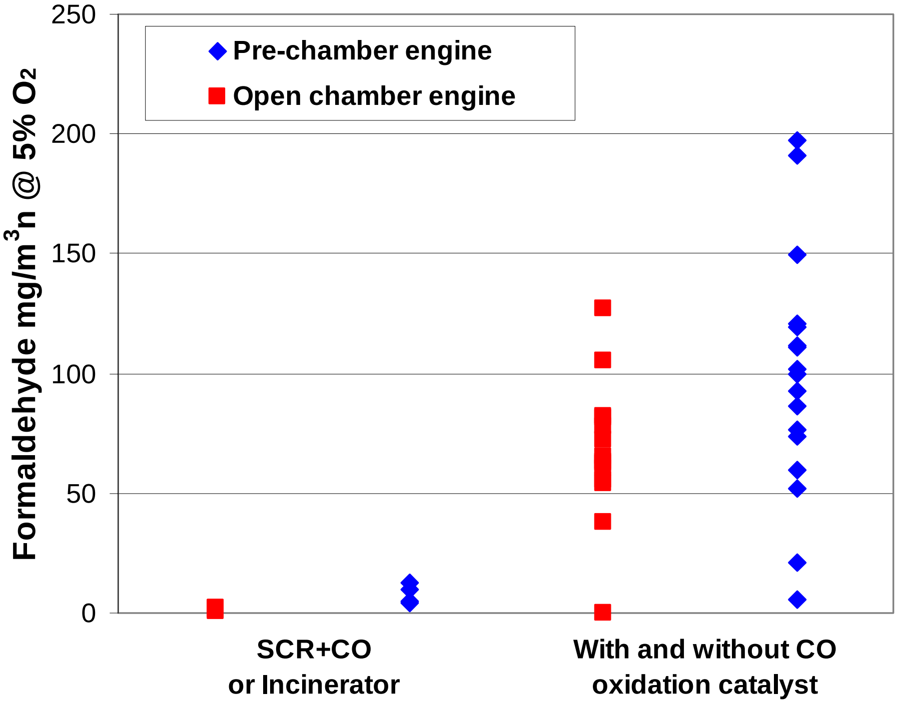

Figure 10 Formaldehyde emission data for natural gas engines. See text for explanation.

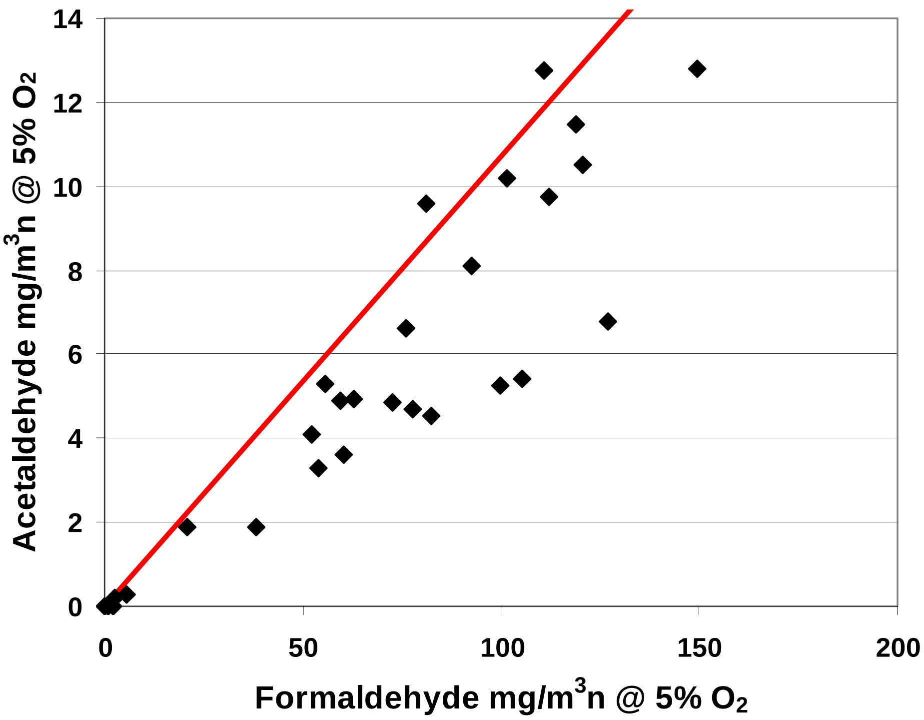

Figure 11 Emission data for acetaldehyde shown as function of formaldehyde emission for natural gas engines. Red line corresponds to methane-ethane ratio in natural gas.

catalyst designed to remove ethene as well. Figure 10 clearly shows that the use of an ordinary CO catalyst is not able to reduce the formaldehyde emission. The new regulation is currently exempted for three years, while DGC and the engine suppliers in Denmark are performing tests with special formaldehyde catalysts. DGC has also performed tests with exhaust gas treatment in a scrubber, where the formaldehyde is absorbed in water with good results. Figure 11 shows that acetaldehyde is formed at a ratio to formaldehyde, which is almost equivalent to the expected ratio compared to the methane-ethane ratio in the natural gas used. The slightly lower ratio of acetaldehyde in the exhaust is probably due to differences in the oxidation behaviour of the components in the exhaust pipe. Emission data has been collected for aldehydes up to benzaldehyde. The correlation to the gas composition is lost for C_3 aldehydes and higher. The aggregated emission factors are given in Appendix A. For a detailed analysis the reader is referred to /1/.

The emission screening study showed that significant amounts of unburned lubrication oil are emitted from the gas engines. The energy averaged emission factor is 12 g/GJ fired. The remaining species were observed in low quantities. This is the case for particulate matter, N_2O, PAH components and for 1.3-butadien. The estimated aggregated emission factors for all components are given in Appendix A.

The natural gas engines in Denmark consumed approximately 35000 TJ of natural gas in year 2000, and the efficiency of electricity production was 38.3% in average. Emission data was available for 18800 TJ or 54% of these for NO_x and CO and 44% for UHC. Odour and aldehyde data were available for 20% and 14%, respectively, and significantly less for the other components.

Emissions During Start and Stop

A few engines were tested during start and stop procedures for emissions of NO_x, CO and UHC. Figure 12 shows an example of the data collected. The emission data was collected together with flow data (gas consumption and O_2 in exhaust) for the engine, making it possible to generate emission factors for start and stop periods based on integrated use of gas for the period and integrated emission. The results show as indicated in Figure 12 that the emissions at start and stop can be significant, compared to the full load emission factors given in Appendix A. The starting and stopping periods are in general in the range of 10-15 minutes for the engines investigated, and one could easily think that the emission at start and stop will be of less significance on an annual basis. This is not the case for the Danish engines. Danish engines operate with approximately one start and stop each day to be able to operate at peak load for the power grid. Annually, this accumulates to 4000 to 6000 hours of operation. The preliminary analysis showed that the annual emissions increased by approximately 1% for NO_x, 5% for UHC and 3% for CO. These are average values, and large differences were observed among the different makes of engines. The issue of start and stop emissions is further actualised by the fact that the power market liberalisation might cause the engines to increase the daily number of starts and stops from approximately one to two or three. This will then need to be taken into account when calculating annual emissions from the plants. DGC plans to perform further investigations in the area to improve the accuracy of the data and to improve the knowledge on engine makes not yet tested.

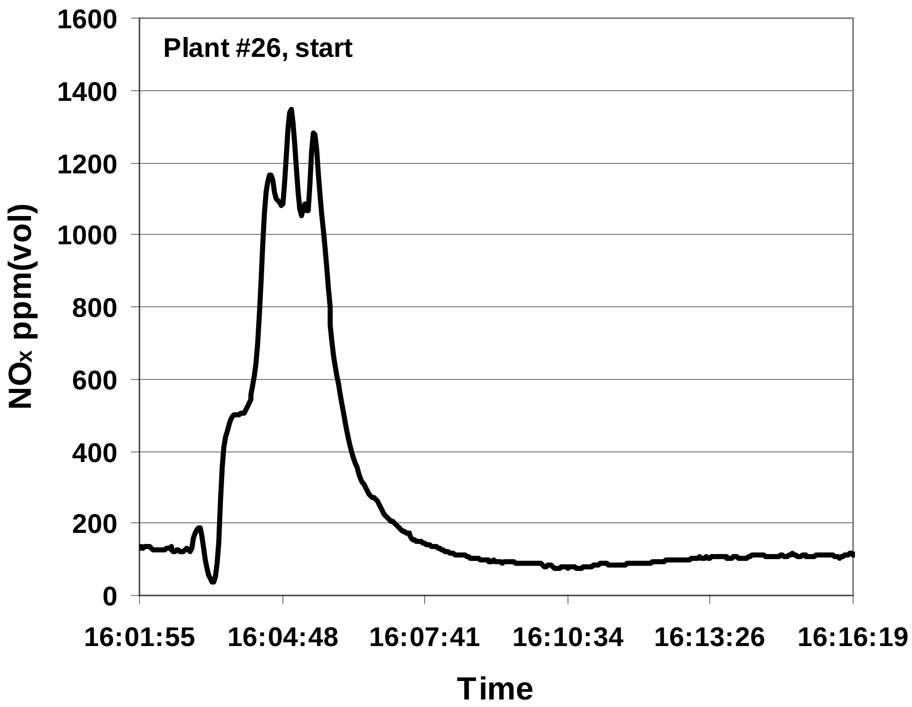

Figure 12 NO_x emission for a natural gas engine during start-up

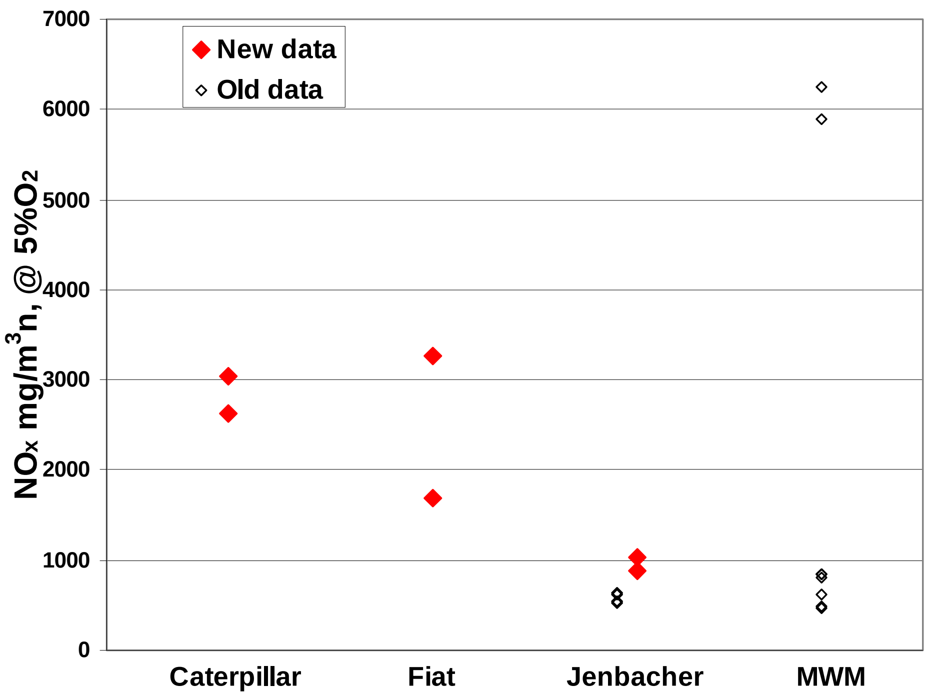

Figure 13 NO_x emission data for biogas engine makes

Biogas Engines

Only a total of 14 old emission data sets considering NO_x, CO and UHC were collected in the project. The low number was caused by the fact that biogas engines do not have emission limits for these components causing fewer measurements to exist. The project supplemented with 7 new measurement series on biogas engines. The biogas is mainly produced from agricultural waste (manure), but also biogas from old waste deposit sites and wastewater treatment plants has been included. The biogas in general contains approximately 65% methane and 35% CO_2.

Figure 13 shows NO_x emission data for biogas engines. The emission level is, in general, higher than for natural gas engines. Plant owners and engine suppliers have taken advantage of the non-regulation to adjust engines for the highest possible efficiency on the biogas. The methane number of the biogas is in the range of 130 making high compression ratios and early spark timing possible without knock problems. Some of the engines have really high emissions of NO_x in the range of several thousands mg/m^3 for several plants. The energy averaged aggregated emission factor was 540 g NO_x/GJ, or more than three times the emission from natural gas engines.

Emissions of CO were also observed to be high. The measuring equipment went into saturation on a couple of plants, causing the estimated emission factor to be a minimum value of 273 g/GJ. The real value is expected to be close to this value. None of the biogas sites is equipped with CO catalyst.

Contrary to the higher NO_x and CO emissions, emissions of UHC and aldehydes are lower on biogas engines. The emission of UHC (almost only methane) is 40% lower for the biogas engines than for the natural gas engines. The emission of formaldehyde is slightly lower than on natural gas engines, but the higher aldehydes are almost absent.

Odour emissions from biogas engines are higher than for natural gas engines. The cause for this is unknown, but the biogas contains some sulphur, mainly as H_2S. The sulphur content may cause formation of species with low odour threshold limits. All estimated emission factors for biogas engines are given in Appendix A.

The total energy consumption on biogas engines accumulated to 2200 TJ in year 2000. Including the project measurements emission measurements were available for 450 TJ or 20%. Biogas engine efficiency was 36.0% on average.

DISCUSSION and CONCLUSION

The newly collected data validated that the existing older emission data could be used for calculations of emission factors. This strongly improves the basis for the emission factors. The fraction of the fuel consumption covered for the major components are summarised in Table 2. As can be seen, emission data is available for a very significant fraction of the fuel consumption. This is especially true for the well known emission of NO_x, CO and UHC. The fraction of plants with measurements for odour and aldehydes is also quite high (10-20% range). For the remaining components shown in Appendix A, typically 1-5% of the fuel consumption on the plants is covered by emission measurements.

Table 2 Fraction of fuel consumption where emission measurements exist

	Unit	Engine	Engine	Turbine
Fuel	**-**	**Natural gas**	**Biogas**	**Natural gas**
NO_x	%	54.2	21.5	67.0
CO	%	54.0	21.5	67.0
UHC	%	43.9	18.3	31.1
Odour	%	20.4	11.3	18.4
Aldehydes	%	14.4	11.3	18.4
Fuel consumption	TJ	34836	2217	9281

All engine sites are rather small; average is around 2 MW electrical, so a substantial amount of measurements is needed if we would improve the data coverage significantly for the major species shown in Table 2. However, for the other species with fewer measurements, a relative improvement in data coverage is possible with a limited number of new measurements.

A first order estimation of the uncertainty on the emission factors has been performed for NO_x and UHC for natural gas engines. A direct deterministic uncertainty calculus is not possible. The major assumption in the calculus is that the engines within a make and model group without available measurements have a similar statistical distribution for the emissions as does the part of the group which has been measured. The emission factor for NO_x was in this study estimated to be 168 g/GJ. This number is based on subgroup aggregation. The uncertainty has been estimated to be ±38 g/GJ on a 95% confidence level. In comparison the emission factor estimated without using subgroups was 181 g/GJ with an uncertainty of ±280 g/GJ on a 95% confidence level. The utilisation of the group homogeneity strongly improves the quality of the emission factor. Table 3 summarise the results for both NO_x and UHC for natural gas engines. Significant improvements on the uncertainty will demand a very large number of new measurements.

Table 3 Emission factors for natural gas engines and the estimated uncertainty on a 95% confidence level

	Unit	With use of sub groups	Without sub groups
NO_x	g/GJ	168±38	181±280
UHC	g/GJ	485±64	531±240

The uncertainty on the species with a lower fraction of measurements (Table 2 or Appendix A) will have larger statistical uncertainties attributed. The emission factors presented, never the less, is the best possible estimate based on the emission measurements available.

When the society framework for the plants changes, emissions change. This is clearly seen in Figure 9 where upcoming stricter emission regulations for CO have caused the installation of a CO catalyst. It is also seen in the analysis of the emissions during start and stop periods. If the liberalisation of the power market causes engines to have significantly more starts and stops, this problem needs further attention. At the same time suppliers introduce new and low emission engines and turbines to the market and old engines are retired. All these factors point to the fact that emission factors will change during the years to come, and in order to have validated emission factors at all times, the emission factors need to be updated in accordance with the changes.

The main conclusion on this work is that it successfully has collected a large number of old and new emission data and from these data validated emission factors for Danish CHP plants were derived. The emission factors found are much better that the previous used guideline values or values from older and less data supported studies.

The screening part of study only revealed a few new components where additional effort is needed. This is true for lubrication oil emission from engines and emission of N_2O from turbines and engines. In general, emissions of the other components were low.

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REFERENCES CITED

/1/ Emission mapping project reports for CHP plants less than 25 MW electrical are available from www.eltra.dk, project 3141. Contact person Kim Behnke kbe@eltra.dk

/2/ Reduction of Emissions from Lean-Burn Gas Engines through Regenerative Incineration and SNCR; P. Kristensen, B. Karll, and G. Horstmann. Presented at the IGRC 2001 in Amsterdam; paper number IUO-18.

APPENDIX A

EMISSION FACTORS

Emission	**Unit**	**Natural gas engine**	**Biogas engine**	**Gas turbine**
NO_x	g/GJ	168	540	124
UHC (as C)	g/GJ	485	254	<2.3
- CH_4	g/GJ	520	323	<1.5
- NMVOC	g/GJ	117	14	<1.4
CO	g/GJ	175	>273	6
N_2O	g/GJ	1.3	0.5	2.2
Total Solid Particulate	g/GJ	0.76	2.63	0.10
PM10	mg/GJ	189	451	61
PM2,5	mg/GJ	161	206	51
PM1	mg/GJ	143	132	38
PAH (benz[a]pyren-equivalent)	mg/GJ	<0.023	<0.003	<0.005
- Naphthalene	mg/GJ	7.9	3.3	0.3
- Acenaphthene	mg/GJ	0.063	0.040	0.021
- Acenaphthylene	mg/GJ	0.043	0.003	0.002
- Anthracene	mg/GJ	0.036	0.004	0.004
- Benz[a]anthracene	mg/GJ	0.009	<0.0004	<0.0007
- Benzo[a]pyrene	mg/GJ	0.003	0.001	0.001
- Benzo[b]fluoranthene	mg/GJ	0.042	0.001	0.001
- Benzo[ghi]perylene	mg/GJ	0.006	<0.0011	<0.003
- Benzo[k]fluoranthene	mg/GJ	0.024	<0.0004	<0.002
- Chrysene	mg/GJ	0.108	0.001	0.001
- Dibenz[a,h]anthracene	mg/GJ	<0.003	<0.0011	<0.003
- Fluoranthene	mg/GJ	0.155	0.006	0.006
- Fluorene	mg/GJ	0.042	0.011	<0.012
- Indeno[1,2,3-cd]pyrene	mg/GJ	0.006	<0.0011	<0.003
- Phenanthrene	mg/GJ	0.440	0.072	0.018
- Pyrene	mg/GJ	0.121	0.002	0.005
Aldehydes				
- Formaldehyde	g/GJ	24	21.15	0.01
- Acetaldehyde	g/GJ	1.88	0.11	0.00
- Acrolein	g/GJ	0.09	0.01	0.00
- Propanal	g/GJ	0.17	0.00	0.00
- Acetone	g/GJ	0.22	0.02	0.01
- Butanal	g/GJ	0.10	0.01	0.01
- Pentanal	g/GJ	0.13	0.00	0.00
- Hexanal	g/GJ	0.02	0.00	0.00
- Benzaldehyde	g/GJ	0.03	0.00	0.00
SO_2	g/GJ	x	19	x
Odour	OU/m^3	8229	18516	2027
Lubrication oil	g/GJ	12	x	x
1,3-butadiene	g/GJ	<0.047	<0.02	x
Efficiency (power)	%	38.3	36.0	28.8
Fuel consumption year 2000	TJ	34836	2217	9281