EMISSIONS FROM DECENTRALISED CHP PLANTS 2007 - ENERGINET.DK ENVIRONMENTAL PROJECT NO. 07/1882

Project report 5 – Emission factors and emission inventory for decentralised CHP production

NERI Technical Report no. 786 2010

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Abstract: Updated emission factors for decentralised combined heat and power (CHP) plants with a capacity < 25MW_e have been estimated based on project emission measurements as well as emission measurements performed in recent years that were collected. The emission factors valid for 2006/2007 have been estimated for the plant technologies: Municipal solid waste (MSW) incineration plants, plants combusting straw or wood, natural gas fuelled reciprocating engines, biogas fuelled engines, natural gas fuelled gas turbines, gas oil fuelled reciprocating engines, gas oil fuelled gas turbines, steam turbines combusting residual oil and reciprocating engines combusting biomass producer gas based on wood. The emission factors for MSW incineration plants are much lower than the emission factors that were estimated for year 2000. The considerable reduction in the emission factors is a result of lower emission limit values in Danish legislation since 2006 that has lead to installation of new and improved flue gas cleaning systems in most MSW incineration plants. For CHP plants combusting wood or straw no major technical improvements have been implemented. The emission factors for natural gas fuelled reciprocating engines have been reduced since year 2000 as a result of technical improvements that have been carried out due to lower emission limit values in Danish legislation. The NO_x emission factor for natural gas fuelled gas turbines has decreased 62 % since year 2000. This is a result of installation of low-NO_x burners in almost all gas turbines that has been necessary to meet new emission limits in Danish legislation. The emission measurements programme included screening of the emissions of HCB, PCB, PCDD/-F and PBDD/-F. Compared to the Danish national emission decentralized CHP plants are major emission sources for CH_4, NO_x, SO_2, heavy metals and HCB.

Keywords:	Emission, emission factor, decentralised heat and power, CHP, emission inventory, gas engine, municipal waste, MSW, incineration, SO_2, NO_x, CH_4, NMVOC, TSP, N_2O, heavy metal, dioxine, aldehyde, HCB, PCB, greenhouse gas, GHG.
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National Environmental Research Institute

NERI Technical reports

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List of abbreviations

BAT	Best Available Technique
BREF	BAT Reference Document
CHP	Combined Heat and Power
CLRTAP	Convention on Long-Range Transboundary Air Pollution
DEA	Danish Energy Agency
DEPA	Danish Environmental Protection Agency
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
HCB	Hexachlorobenzene
IPCC	Intergovernmental Panel on Climate Change
NMVOC	Non Methane Volatile Organic Compounds
OU	Odour unit
PAH	Polycyclic Aromatic Hydrocarbon
PBDD/-F	Poly Brominated Dibenzo Dioxins and Furans
PCB	Polychlorinated biphenyl
PCDD/-F	Poly Chlorinated Dibenzo Dioxins and Furans
POP	Persistent Organic Pollutant
TSP	Total Suspended Particulates
UFP	Ultra Fine Particles
UHC	Unburned hydrocarbons
UNECE	United Nations Economic Commission for Europe

Preface

The Danish Gas Technology Centre (DGC), FORCE Technology (FORCE), AnalyTech and the National Environmental Research Institute (NERI) at Aarhus University (AU) have conducted a survey of emissions from decentralised CHP plants. The project is funded by Energinet.dk.

The purpose of the project has been to derive updated emission factors and to point out the major environmental impacts from Combined Heat and Power (CHP) plants (< 25 MW_e) in Denmark. An additional goal of the project has been to screen for pollutants that have not been measured previously, in order to evaluate their significance.

The project is reported in six project reports that will be published at the website of Energinet.dk. This report includes estimation of emission factors and an emission inventory for decentralised CHP production in 2006.

In connection with the project an advisory board was established with representation from the industry as well as representatives from public and private institutions.

The following participated in the advisory board:

Hanne Johnsen	waste denmark (affald danmark)
J. Vitus Nielsen	Babcock & Wilcox Vølund
Helga Moos	Brancheforeningen for Decentral Kraftvarme
Peter Arendt Jensen	Technical University of Denmark, Department of Chemical and Biochemical Engineering
John Tang	Danish District Heating Association
Lars Gissel	E.ON Denmark
Anders Schmidt Dideriksen	E.ON Denmark
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Kjeld Skærbæk Nielsen	Rolls-Royce Marine A/S
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Anders Christiansen	Local Government Denmark

External expert review of the Danish version of this report was conducted by Jytte Boll Illerup, Technical University of Denmark, Department of Chemical and Biochemical Engineering.

Summary

A revised set of emission factors for decentralized combined heat and power (CHP) plants <25MW_e has been estimated. The emission factors valid for 2006/2007 have been estimated for the plant technologies: Municipal solid waste (MSW) incineration plants, plants combusting straw or wood, natural gas fuelled reciprocating engines, biogas fuelled engines, natural gas fuelled gas turbines, gas oil fuelled reciprocating engines, gas oil fuelled gas turbines, steam turbines combusting residual oil and reciprocating engines combusting biomass producer gas based on wood.

The emission factors have been estimated based on emission measurements performed as part of the project as well as emission measurements that have been collected by FORCE Technology (FORCE) and Danish Gas Technology Centre (DGC). Further the estimates have been based on plant specific fuel consumption data collected annually by the Danish Energy Agency (DEA).

An extract of the revised 2006/2007 emission factors is shown in Table 1.

Table 1 Extract of the revised 2006 (2007 for natural gas fuelled plants) emission factors for Danish decentralised CHP plants < 25MW$_e$.

	Unit	Natural gas fuelled engines	Biogas fuelled engines	Natural gas fuelled gas turbines	Gas oil fuelled engines	Gas oil fuelled gas turbines	Fuel oil, steam turbines	Biomass producer gas, engines	MSW incinera-tion	Straw	Wood
SO_2	g per GJ	-	-	-	-	-	-	-	< 8.3	49	< 1.9
NO_x	g per GJ	135[8)]	202	48	942	83	136	173	102	125	81
UHC (C)	g per GJ	435[8)]	333	2.5[9)]	(46) [10)]	-	(1.6) [10)]	12	< 0.68	< 0.94[5)]	< 6.1[6)]
NMVOC	g per GJ	92[4) 8)]	10[4)]	1.6[4)]	(37)[10)]	-	(0.8) [10)]	2.3[4)]	< 0.56[4)]	< 0.78[4)]	< 5.1[4)]
CH_4	g per GJ	481[4) 8)]	434[4)]	1.7[4)]	24	-	< 1.3	13[4)]	< 0.34[4)]	< 0.47[4)]	< 3.1[4)]
CO	g per GJ	58[8)]	310	4.8	130	2.6	2.8	586	< 3.9	67	90
N_2O	g per GJ	0.58	1.6	1.0	2.1	-	5.0	2.7	1.2	1.1	0.83
NH_3	g per GJ	-	-	-	-	-	-	-	< 0.29	-	-
TSP	g per GJ	-	-	-	-	-	9.5	-	< 0.29	< 2.3	10
As	mg per GJ	< 0.045	< 0.042	-	< 0.055	-	-	0.116	< 0.59	-	-
Cd	mg per GJ	< 0.003	0.002	-	< 0.011	-	-	< 0.009	< 0.44	< 0.32[3)]	0.27
Co	mg per GJ	< 0.20	< 0.21	-	< 0.28	-	-	< 0.22	< 0.56	-	-
Cr	mg per GJ	0.048	0.18	-	0.20	-	-	0.029	< 1.6	-	-
Cu	mg per GJ	0.015	0.31	-	0.30	-	-	< 0.045	< 1.3	-	-
Hg	mg per GJ	< 0.098[3)]	< 0.12	-	< 0.11	-	-	0.54	< 1.8	< 0.31[3)]	< 0.40[3)]
Mn	mg per GJ	< 0.046	0.19	-	0.009	-	-	0.008	< 2.1	-	-
Ni	mg per GJ	0.045	0.23	-	0.013	-	-	0.014	< 2.1	-	-
Pb	mg per GJ	0.043	0.005	-	0.15	-	-	0.022	< 5.5	-	-
Sb	mg per GJ	< 0.049[3)]	0.12	-	< 0.055	-	-	< 0.045	< 1.1	-	-
Se	mg per GJ	(0.01)[7)]	< 0.21	-	< 0.22	-	-	< 0.18	< 1.1	-	-
Tl	mg per GJ	< 0.20[3)]	< 0.21	-	< 0.22	-	-	< 0.18	< 0.45[3)]	-	-
V	mg per GJ	< 0.048	< 0.042	-	0.007	-	-	< 0.045	< 0.33	-	-
Zn	mg per GJ	2.9	4.0	-	58	-	-	0.058	2.3	0.41	2.3
PCDD/-F	ng per GJ	< 0.57	< 0.96[1)]	-	< 0.99	-	-	< 1.7[1)]	< 5.0	< 19	< 14
PBDD/-F	ng per GJ	-	< 5.0[1)]	-	-	-	-	< 7.2[1)]	< 6.3[1)]	-	-
PAH (BaP)	µg per GJ	< 13	< 4.2	-	< 33	-	-	< 4.9	< 2	< 125	< 13
ΣPAH	µg per GJ	< 1025	< 606	-	< 8988	-	-	< 181	< 37	< 5946	< 664
Naphthalene	µg per GJ	2452	4577	-	17642	-	-	8492	< 129[3)]	12088	2314
HCB	µg per GJ	-	0.19	-	< 0.22	-	-	0.80	< 4.3	< 0.11	-
PCB	ng per GJ	-	< 0.19[1)]	-	< 0.13[1)]	-	-	< 0.24[1)]	< 0.32	-	-
Formalde-hyde	g per GJ	14.1	8.7	-	1.3	-	< 0.002	1.5	-	-	-
HCl	g per GJ	-	-	-	-	-	-	-	< 1.14	56	-
HF	g per GJ	-	-	-	-	-	-	-	< 0.14	-	-

[1)] Emission measurements were below detection limits for all congeners.
[2)] Based on 1 emission measurement. The emission measurement was below the detection limit.
[3)] All emission measurements were below the detection limit.
[4)] Based on disaggregation of the total unburned hydrocarbon (UHC) emission factor.
[5)] Only 1 out of 7 emission measurement was above the detection limit.
[6)] Two out of three emission measurements were below the detection limit.
[7)] Two emission measurements were performed, both below the detection limit. These results have been ignored and instead the lower emission factor 0.01 mg per GJ based on EEA (2009) have been applied.
[8)] The increased emission level during start up and stop of the gas engines have been included in this emission factor.
[9)] Based on emission measurements performed in 2003-2006.
[10)] The emission factor based on emission measurements performed within this project has been ignored. Instead the NMVOC emission factor refers to EEA (2009). The UHC emission factor has been estimated based on the emission factors for NMVOC and CH_4.

The emission factors for MSW incineration plants are much lower than the emission factors that were estimated for year 2000. The considerable reduction in the emission factors is a result of lower emission limit values in Danish legislation (MST, 2003) since 2006 that has lead to installation of new and improved flue gas cleaning systems in most MSW incinera-

tion plants. The Total Suspended Particulates (TSP) emission factor is 86 % lower than the emission factor in year 2000, whereas the reduction for heavy metal emission factors is 38 % to 96 %. For dioxin (PCDD/-F) the emission factor has decreased 97 % since 2000 due to the fact that dioxin flue gas cleaning has been installed in all MSW incineration plants as a result of the new emission limit values (DEPA, 2003). The NO_x emission factor has decreased 17 % since 2000. Emission factors for SO_2, HCl and HF have also decreased considerably since 2000.

Combined heat and power (CHP) plants combusting straw and wood have not undergone major changes in technology or flue gas cleaning systems since 2000 and the emission limit values are also unchanged. The relatively low number of plants and emission measurements result in uncertainty concerning development of the emission levels of these plant categories. Emission measurements from 2000-2008 have been included in the estimates.

The emission factors for natural gas fuelled reciprocating engines have been reduced since 2000 as a result of technical improvements that have been carried out as a result of lower emission limit values in Danish legislation (DEPA, 2005). Most engines had to be below the lower emission limit values in October 2006 and thus the emission factors have been estimated for 2007 onwards. The NO_x emission factor has decreased 20 % and the CO emission factor has decreased 68 % since 2000. Oxidation catalysts for reduction of the emission of CO have now been installed at all natural gas fuelled engine plants. The Unburned hydrocarbons (UHC) emission has also decreased since 2000. The CH_4 emission factor has decreased 10 % and the NMVOC 24 %.

The fuel consumption for biogas fuelled engines has increased 32 % since 2000. The increase is mainly on larger engines. This is part of the reason for the changes of emission factors for biogas fuelled engines. Lower emission limit values for biogas fuelled engines > 1 MW is included in Danish legislation (DEPA, 2005), but the engines do not have to meet these emission limits until 2013. The emission factor for NO_x has decreased 63 % since 2000 whereas the emission factor for UHC has increased 31 %. The CO emission factor is 14 % higher than in 2000.

The NO_x emission factor for natural gas fuelled gas turbines has decreased 62 % since 2000. This is a result of installation of low-NO_x burners in almost all gas turbines. This has been necessary to meet new emission limits in Danish legislation (DEPA, 2005).

Emission factors have also been estimated for CHP plants combusting oil and biomass producer gas respectively. For gas oil fuelled engines the NO_x emission factor is remarkably high compared to other CHP plants. The CO emission factor for engines fuelled by biomass producer gas is considerably higher than for other engines whereas the UHC emission is much lower. This is in agreement with the composition of the biomass producer gas.

The emission measurements performed in this project included screening of a number of emissions that have not previously been measured from Danish CHP plants. The measurements for brominated dioxins/furans (PBDD/-F) were below the detection limits for all congeners. The detec-

tion limit for PBDD/-F was higher than the detection limit for PCDD/-F and thus the data for PBDD/-F added limited new information. Based on the PBDD/-F emission measurements performed in this project it could not even be rejected that the PBDD/-F emission is higher than the PCDD/-F emission.

A few PCDD/-F congeners were above the detection limit for gas oil fuelled engines and natural gas fuelled engines whereas all congeners were below the detection limit for biomass producer gas fuelled engines. Further PCDD/-F emissions above the detection limit were measured for MSW incineration plants and for straw and wood fuelled CHP plants.

PCB emission measurements performed at engines fuelled by gas oil, biogas and biomass producer gas were below the detection limit for all congeners. For MSW incineration plants several PCB emission measurements were above the detection limit. The PCB emission factors are below the emission factors stated in a former study (Thomsen et al., 2009).

As expected MSW incineration plants are the main emission source for HCB. In spite of the fact that the estimated HCB emission factor for MSW incineration is much lower than the current factor MSW incineration is still among the main emission sources for HCB in Denmark.

Uncertainty estimates for the emission factors have been estimated and reported in project report 3 (Boje et al., 2010b) and project report 4 (Jørgensen et al., 2010b).

Total emissions from decentralized CHP plants <25MW_e have been estimated for 2006. This estimate shows that natural gas fuelled engines was the main emission source for CH_4, NMVOC and aldehydes. Further, natural gas fuelled engines was the largest emission source for CO (49 %) and NO_x (41 %) and, unexpectedly, also for Zn (34%). MSW incineration plants were the main source of emission for most heavy metals, HF, PCDD/-F, HCB and PCB. Further the emissions of NO_x (37 %) and SO_2 (23 %) were also considerable. Wood fired CHP plants was the main emission source for particulates (TSP). Both wood and straw fired CHP plants were considerable emission sources for PCDD/-F. Steam turbines fuelled by residual oil was the main emission source for SO_2 and several heavy metals. Biogas fuelled engines was a considerable emission source for CO (29 %) whereas emissions of all other pollutants were low. Emissions from natural gas fuelled gas turbines and from engines fuelled by gas oil or biomass producer gas were all relatively low.

The emission of NO_x and SO_2 from decentralized CHP plants <25MW_e added up to 5 % of the total Danish emission. The CH_4 emission added up to 6 % of the national emission whereas the emission of several heavy metals was above 10 %. The HCB emission added up to 30 % of the national emission but it has to be taken into account that all HCB emission sources have not yet been included in the national inventory. The emission of dioxin (PCDD/-F) added up to only 1 % of the national emission whereas the emission share was approximately 35 % in 1995.

The emissions from decentralised CHP plants have been compared to the emission from Danish public electricity and heat production. The decentralized CHP plants are a major emission source for CH_4 and NMVOC.

Further the decentralized CHP plants are large emission sources for NO_x, CO, heavy metals, PCDD/-F and HCB.

Sammendrag

Der er blevet udarbejdet opdaterede emissionsfaktorer for decentrale kraftvarmeværker < 25 MW_e for år 2006/2007. Emissionsfaktorerne omfatter følgende typer af decentrale kraftvarmeværker: affaldsforbrændingsanlæg, halmfyrede værker, træfyrede værker, naturgasdrevne motorer, biogasdrevne motorer, naturgasdrevne gasturbiner, gasoliedrevne motorer, gasoliedrevne gasturbiner, fueloliedrevne dampturbiner samt motorer der anvender forgasningsgas baseret på træ.

Emissionsfaktorerne er udarbejdet på basis af såvel indsamlede emissionsdata som projektmålinger. Endvidere er emissionsfaktorerne baseret på en energivægtning i henhold til Energistyrelsens energiproducenttælling for 2006.

Et uddrag af emissionsfaktorerne for år 2006 er vist i tabel 1. Emissionsfaktorerne for naturgasdrevne motorer og turbiner er dog bestemt for år 2007, fordi der for disse anlægstyper er nye emissionsgrænseværdier gældende fra 2007.

Tabel 1 Uddrag af emissionsfaktorerne for decentrale kraftvarmeværker < 25MW$_e$, 2006 (2007 for naturgas).

	Enhed	Natur-gas-motorer	Biogas-motorer	Natur-gasdrev-ne turbi-ner	Gasolie-drevne motorer	Gasolie drevne turbiner	Fuelolie, damp-turbine	For-gasnings-gas, motorer	Affaldsfor-brænd-ings-anlæg	Halm	Træ
SO_2	g per GJ	-	-	-	-	-	-	-	< 8,3	49	< 1,9
NO_x	g per GJ	135[8)]	202	48	942	83	136	173	102	125	81
UHC (C)	g per GJ	435[8)]	333	2,5[9)]	(46) [10)]	-	(1,6) [10)]	12	< 0,68	< 0,94[5)]	< 6,1[6)]
NMVOC	g per GJ	92[4) 8)]	10[4)]	1,6[4)]	(37)[10)]	-	(0,8) [10)]	2,3[4)]	< 0,56[4)]	< 0,78[4)]	< 5,1[4)]
CH_4	g per GJ	481[4) 8)]	434[4)]	1,7[4)]	24	-	< 1,3	13[4)]	< 0,34[4)]	< 0,47[4)]	< 3,1[4)]
CO	g per GJ	58[8)]	310	4,8	130	2,6	2,8	586	< 3,9	67	90
N_2O	g per GJ	0,58	1,6	1,0	2,1	-	5,0	2,7	1,2	1,1	0,83
NH_3	g per GJ	-	-	-	-	-	-	-	< 0,29	-	-
TSP	g per GJ	-	-	-	-	-	9,5	-	< 0,29	< 2,3	10
As	mg per GJ	< 0,045	< 0,042	-	< 0,055	-	-	0,116	< 0,59	-	-
Cd	mg per GJ	< 0,003	0,002	-	< 0,011	-	-	< 0,009	< 0,44	< 0,32[3)]	0,27
Co	mg per GJ	< 0,20	< 0,21	-	< 0,28	-	-	< 0,22	< 0,56	-	-
Cr	mg per GJ	0,048	0,18	-	0,20	-	-	0,029	< 1,6	-	-
Cu	mg per GJ	0,015	0,31	-	0,30	-	-	< 0,045	< 1,3	-	-
Hg	mg per GJ	< 0,098[3)]	< 0,12	-	< 0,11	-	-	0,54	< 1,8	< 0,31[3)]	< 0,40[3)]
Mn	mg per GJ	< 0,046	0,19	-	0,009	-	-	0,008	< 2,1	-	-
Ni	mg per GJ	0,045	0,23	-	0,013	-	-	0,014	< 2,1	-	-
Pb	mg per GJ	0,043	0,005	-	0,15	-	-	0,022	< 5,5	-	-
Sb	mg per GJ	< 0,049[3)]	0,12	-	< 0,055	-	-	< 0,045	< 1,1	-	-
Se	mg per GJ	(0,01)[7)]	< 0,21	-	< 0,22	-	-	< 0,18	< 1,1	-	-
Tl	mg per GJ	< 0,20[3)]	< 0,21	-	< 0,22	-	-	< 0,18	< 0,45[3)]	-	-
V	mg per GJ	< 0,048	< 0,042	-	0,007	-	-	< 0,045	< 0,33	-	-
Zn	mg per GJ	2,9	4,0	-	58	-	-	0,058	2,3	0,41	2,3
PCDD/-F	ng per GJ	< 0,57	< 0,96[1)]	-	< 0,99	-	-	< 1,7[1)]	< 5,0	< 19	< 14
PBDD/-F	ng per GJ	-	< 5,0[1)]	-	-	-	-	< 7,2[1)]	< 6,3[1)]	-	-
PAH (BaP)	µg per GJ	< 13	< 4,2	-	< 33	-	-	< 4,9	< 2	< 125	< 13
ΣPAH	µg per GJ	< 1025	< 606	-	< 8988	-	-	< 181	< 37	< 5946	< 664
Naphthalen	µg per GJ	2452	4577	-	17642	-	-	8492	< 129[3)]	12088	2314
HCB	µg per GJ	-	0,19	-	< 0,22	-	-	0,80	< 4,3	< 0,11	-
PCB	ng per GJ	-	< 0,19[1)]	-	< 0,13[1)]	-	-	< 0,24[1)]	< 0,32	-	-
Formalde-hyd	g per GJ	14,1	8,7	-	1,3	-	< 0,002	1,5	-	-	-
HCl	g per GJ	-	-	-	-	-	-	-	< 1,14	56	-
HF	g per GJ	-	-	-	-	-	-	-	< 0,14	-	-

[1)] Målingerne var under detektionsgrænsen for alle kongenere.
[2)] Baseret på en enkelt måling der var under detektionsgrænsen.
[3)] Alle målinger under detektionsgrænsen.
[4)] Baseret på en fordelingsnøgle for UHC.
[5)] Kun en enkelt af i alt 7 målinger er over detektionsgrænsen.
[6)] To ud af tre målinger under detektionsgrænsen.
[7)] Der er foretaget to målinger der begge var under detektionsgrænsen. Der er set bort fra den estimerede emissionsfaktor og i stedet anvendes emissionsfaktoren 0,01 mg per GJ (EEA, 2009).
[8)] Forhøjet emission under start og stop er indregnet.
[9)] Baseret på data fra 2003-2006.
[10)] Der er set bort fra projektets måleresultater og i stedet anvendes emissionsfaktorer for NMVOC fra EEA (2009). UHC emissionsfaktoren er beregnet på basis af NMVOC og CH_4 emissionsfaktorerne.

Generelt er emissionsfaktorerne for affaldsforbrænding væsentligt lavere end de emissionsfaktorer, der tidligere er fastlagt for år 2000. Den store reduktion af emissionerne er et resultat af nye emissionsgrænseværdier i affaldsbekendtgørelsen, Bekendtgørelse 162 (MST, 2003), der har medført ombygning af røggasrensningsanlæggene på de fleste affaldsforbrændingsanlæg. Emissionsfaktoren for partikler (TSP) er 86 % lavere end i år 2000, mens reduktionen for tungmetallerne er på 38 % til 96 %. For dioxin (PCDD/-F) er emissionsfaktoren 97 % lavere, og det hænger sammen

med, at alle affaldsforbrændingsanlæg nu, pga. grænseværdierne i Bekendtgørelse 162, er blevet forsynet med dioxinrensning. NO_x-emissionsfaktoren er 17 % lavere end i år 2000. Emissionsfaktorerne for SO_2, HCl og HF er ligeledes reduceret væsentligt siden år 2000.

For halm- og træfyrede anlæg er der ikke nye emissionsgrænseværdier, og der har ikke været større anlægsændringer siden år 2000. De relativt få anlæg og målinger gør, at det ikke med sikkerhed kan konkluderes, at der har været en udvikling i retning af højere eller lavere emissioner. Ældre emissionsdata er blevet inddraget i datagrundlaget. Der har vist sig at være store variationer i emissionsniveauet for det enkelte anlæg.

Emissionsfaktorerne for naturgasdrevne motorer er reduceret siden 2000 som et resultat af de tekniske ændringer af motorerne, som de nye emissionsgrænseværdier i Bekendtgørelse 621 (MST, 2005) har nødvendiggjort. De nye emissionsgrænseværdier var for de fleste motorer gældende fra oktober 2006. NO_x-emissionsfaktoren er således faldet med 20 % og CO-emissionsfaktoren er faldet med 68 % siden 2000. Det store fald i CO-emissionsfaktoren skyldes, at alle motorerne nu er forsynet med oxidationskatalysator. UHC-emissionen er ligeledes faldet siden 2000. CH_4-emissionsfaktoren er faldet 10 %, mens emissionsfaktoren for NMVOC er faldet 24 %.

Brændselsforbruget for biogasdrevne motorer er steget med 32 % siden 2000, og det er især forbruget på større motorer der er steget. Dette kan være en del af grunden til de ændringer, der har været i emissionsfaktorerne for biogasdrevne motorer. Biogasdrevne motorer > 1 MW er omfattet af Bekendtgørelse 621 (MST, 2005), men de nye grænseværdier er først gældende fra 2013. Emissionsfaktoren for NO_x er faldet 63 % siden 2000, mens emissionsfaktoren for UHC er steget 31 %. CO-emissionsfaktoren er 14 % højere end i 2000.

NO_x-emissionsfaktoren for naturgasdrevne turbiner er faldet 62 % siden 2000. Dette er igen et resultat af Bekendtgørelse 621 (MST, 2005) der har betydet, at stort set alle gasturbinerne er blevet forsynet med low-NO_x-brændere.

Der er blevet fastlagt emissionsfaktorer for oliedrevne anlæg og for motorer, der anvender forgasningsgas baseret på træ. For oliedrevne motorer er specielt emissionsfaktoren for NO_x bemærkelsesværdig, idet den er langt højere end for alle de øvrige anlægstyper. Emissionsfaktoren for CO fra motorer der anvender forgasningsgas, er meget højere end fra de øvrige gasmotorer, mens UHC-emissionen er meget lavere. Dette stemmer overens med forgasningsgassens sammensætning, idet der er et stort indhold af CO og et lavt indhold af kulbrinter.

Måleprogrammet for projektmålingerne omfattede screening for en række emissionskomponenter. Alle målinger for bromerede dioxiner og furaner (PBDD/-F) var under detektionsgrænsen for alle kongenere. Detektionsgrænsen for PBDD/-F viste sig at være højere end detektionsgrænsen for PCDD/-F. En sammenligning af emissionsbidraget fra henholdsvis PBDD/-F og PCDD/-F er på denne baggrund vanskelig, og det kan ikke på baggrund af datasættet afvises, at emissionen af PBDD/-F overstiger emissionen af PCDD/-F. For PCDD/-F er der detekteret enkelte kongenere for gasoliedrevne motorer og naturgasmotorer, hvorimod alle

kongenere var under detektionsgrænsen for såvel forgasningsgasdrevne motorer som biogasdrevne motorer. Endvidere er der måledata over detektionsgrænsen for affald, halm og træ.

PCB-målingerne fra gasoliedrevne motorer, biogasdrevne motorer og forgasningsgasdrevne motorer var alle under detektionsgrænsen for alle kongenere. For affaldsforbrænding var kun en enkelt prøve under detektionsgrænsen for alle kongenere, mens flere PCB'er kunne detekteres i de øvrige målinger. PCB-emissionsfaktorerne er langt under de emissionsfaktorer som tidligere studier har angivet (Thomsen et al., 2009).

HCB-emissionen er som ventet størst fra affaldsforbrænding. Selvom HCB-emissionen er betydeligt lavere end hidtil estimeret, er affaldsforbrænding blandt de største kilder til HCB-emission i Danmark.

Der er foretaget vurdering af usikkerhed for emissionsfaktorerne i projektets delrapport 3 (Boje et al., 2010b) og delrapport 4 (Jørgensen et al., 2010b).

Der er udarbejdet en samlet emissionsopgørelse for decentral kraftvarme år 2006. Denne viser, at naturgasdrevne motorer var langt den største kilde til emission af CH_4, NMVOC og aldehyder. Gasmotorerne var endvidere den største emissionskilde for CO (49 %) og NO_x (41 %) samt lidt uventet også for Zn (34 %). Affaldsforbrændingsanlæg var den største kilde til emission af de fleste metaller, HF, PCDD/-F, HCB og PCB. Endvidere var der et højt emissionsbidrag for NO_x (37 %) og SO_2 (23 %). Halmfyrede værker var den største emissionskilde for HCl. Træfyrede værker var den største kilde til partikelemission (TSP). Både træ- og halmfyrede værker var desuden væsentlige kilder til emissionen af PCDD/-F. Fueloliefyrede dampturbiner var den største kilde til SO_2-emission og til emissionen af flere metaller. Biogasdrevne motorer var i 2006 en væsentlig kilde til CO-emission (29 %), men ellers var emissionsandelen fra biogasdrevne motorer begrænset. Emissionsbidragene fra naturgasdrevne turbiner samt anlæg der anvender gasolie eller forgasningsgas var lave.

Emissionen af NO_x fra decentral kraftvarme udgjorde i 2006 5 % af den samlede danske emission. SO_2 udgjorde ligeledes 5 % af den nationale emission. CH_4-emissionen udgjorde 6 % af den nationale emission, mens emissionen af flere metaller lå over 10 %. Emissionsbidraget af HCB var i 2006 helt oppe på 30 %, men her skal det bemærkes, at ikke alle emissionskilder er inkluderet i de nationale opgørelser. Emissionsandelen for dioxin var helt nede på 1 %, hvilket er et betydeligt fald siden 1995 hvor andelen var på ca. 35 %.

Sammenholdes emissionen fra decentral kraftvarme med øvrige elproducerende anlæg fremgår det, at CH_4- og NMVOC-emissionen fra de decentrale værker er relativt høj. Derudover er de decentrale værker en væsentlig emissionskilde for NO_x, CO, metaller, PCDD/-F og HCB.

1 Introduction

In the project "Survey of emissions from decentralised CHP plants" funded by Eltra (PSO project 3141) emission factors[1] for decentralised CHP production (<25 MW_e) were estimated. The technological development since then has necessitated an update of the emission factors. For several plant types new emission limit values have come into force since 2003.

In addition to updating the previous estimated emission factors there was a need to include emission factors for oil fuelled plants and for gas engines powered by biomass producer gas, since these plant types were not included in the earlier project.

The emission factors are used by Energinet.dk in elaborating their yearly environmental report. This reporting includes an environmental impact statement for electricity and an inventory of the total emission associated with production of electricity in Denmark. I 2008 20 % of the electricity production in Denmark was based on decentralised CHP production (Energinet.dk 2009). It is therefore important for Energinet.dk to have reliable and well-documented emission factors for this category of plants.

NERI uses the emission factors in the national emission inventory, which is reported annually to the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP), the EU National Emission Ceilings Directive (NECD), the EU Monitoring Mechanism (EUMM) and the UN Framework Convention on Climate Change (UNFCCC).

[1] Emission factors valid for the year 2000.

2 Data sources

The basic energy data used in the project is a data set for 2006 by the Danish Energy Agency (DEA 2007). Additionally emission measurements from the period 2003-2009 and databases containing information on technology and flue gas cleaning for the different plants are used. The emission measurements include measurements done within the project as well as existing measurement reports collected during the project.

2.1 Energy statistics

The Danish Energy Agency (DEA) annually updates a survey that includes plant specific data for all plants that produces electricity and/or district heating. The Danish Energy Agency has provided the project with a copy of the survey for 2006. The survey includes information on plant type, fuel consumption, electricity and heat production, and capacity of the plants[2].

The basis for estimating emission factors has been the survey for 2006 (DEA, 2007). All plants with an electric effect below 25 MW were selected under the condition that the plant had a consumption of one or a few of the following fuels: natural gas, biogas, biomass producer gas (based on gasification of wood), gas oil, fuel oil, waste, straw and wood. Some plants are combusting coal with a capacity below 25 MW_e; however these plants were not included.

In the DEA survey the wood consumption is divided into wood pellets, wood chips and wood waste. For the purpose of this project these fuels have simply been considered as wood. This is due to the relatively small number of wood fired plants.

2.2 Emission measurements

The basis for estimating emission factors includes both existing measurements carried out in recent years and measurements performed in this project.

An overview of the number of plants included in the estimation of emission factors is shown in Chapter 4.

2.2.1 Existing measurements

The existing measurements were collected in the initial stage of this project. Most of the measurements have been performed as documentation to the licensing authority and have been carried out by companies accredited to perform emission measurements and analyses.

[2] Generally the survey is divided into single engines, boilers etc. For some plants several production units are aggregated in one record.

FORCE has collected existing data for waste incineration plants and biomass fired plants. The measurements have either been performed by FORCE or AnalyTech. The data available is presented in project report 1 (Boje et al., 2010a). There is data available for 15[3] waste incineration lines on 10 plants, two straw fired plants and one wood fired plant. The measurements included in the data set are from the period 2006-2009. Due to the very limited number of data sets available for biomass fired plants NERI has decided to include the data collected during the previous project reported in 2003. This has been further discussed in Chapter 5.4 and 5.5.

DGC has collected data from previous measurements on natural gas powered gas engines, biogas powered gas engines and gas turbines. Additionally accredited emission measurement reports have been provided by several gas engine manufacturers. In addition emission measurement data were available for oil powered plants and from an engine using biomass producer gas. The collected data is from the period 2003-2008. In total 670 data sets have been collected, some of which represent multiple measurements on the same engine/turbine. The data is presented in project report 2 (Jørgensen et al., 2010a).

2.2.2 Project measurements

The project measurements were all performed in 2008-2009. DGC has made the measurements on plants using natural gas, biogas, biomass producer gas and oil. AnalyTech has made the measurements on plants using waste, straw and wood. For each project measurement an emission measurement report has been published (Degn & Lykke, 2009; Andersen et al., 2009).

The measurement reports do not include plant name. Instead the emission measurements only relate to fuel, plant type and flue gas cleaning. The project measurements have been carried out on plants that applies technologies that represent a major part of the fuel consumption or on plants that applies technologies that are poorly represented in the existing measurement data.

Measurements have been carried out at 25 plants in total:

- 3 waste incineration plants
- 3 biomass fired plants, 1 wood fired and 2 straw fired
- 9 natural gas powered engines
- 3 biogas powered engines, using biogas based on manure, landfill gas or gas from wastewater treatment
- 3 natural gas powered gas turbines
- 2 gas oil powered engines
- 1 fuel oil powered steam turbine
- 1 gas engine combusting biomass producer gas based on wood

[3] Plants where measurements have been carried out on a shared stack, have been calculated as one line.

The full measurement programme is included in Appendix 14. Some of the measurements include special compounds, e.g. HCB, PCBs and PBDD/-F.

2.2.3 Pollutants covered

Emissions of the following pollutants are included: SO_2, NO_x, NMVOC, CH_4, CO, N_2O, NH_3, particulate matter (TSP), metals (As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Sb, Se, Sn, Tl, V and Zn), (PCDD/-F)[4], (PBDD/-F)[4], PAH[4], aldehydes[4], HCl, HF, HCB and PCB[4]. For further information see Chapter 5.1.

The existing measurements have not been as exhaustive regarding the coverage of pollutants as the project measurements. Therefore the basis for estimating emission factors for e.g. NO_x and TSP is more solid than e.g. the basis for PAH. Several of the measurements of special pollutants e.g. HCB, PCB and PBDD/-F are included primarily to establish the emission level and subsequently to evaluate whether the emission levels are problematic.

Emissions of PAH are listed in the main report as ΣPAH and PAH (BaP). ΣPAH is a simple sum of the 15 PAH compounds analysed. PAH (BaP) is the PAH emission expressed in benzo(a)pyrene equivalents. Measurement data for the single compounds and the toxicity factors used are included in Appendix 11.

Emissions of PCDD/-F are listed in international toxic equivalents (I-Teq). Information on the single congeners and the toxic equivalence factors are included in Appendix 11.

[4] Includes several congeners, see Appendix 13.

3 Plant technologies

For every plant type subdivisions have been made for groups of plants considered to be similar in terms of emission characteristics. These subdivisions have been used when aggregating emission factors for the overall plant type. In the following paragraphs the plant types and the subdivisions used are described. Furthermore, the fuel consumption for the different plant types has been listed.

3.1 Waste incineration plants

The waste incineration plants are subdivided based on the type of desulphurisation, different type of particle abatement and if the plant is equipped with $DeNO_x$.

There are three different types of desulphurisation used:

- Wet desulphurisation
- Semi-dry desulphurisation
- Dry desulphurisation

Three different types of particle abatement and combinations hereof are in use:

- Electrostatic precipitator
- Filter bag
- Cyclone

Finally a separation is made based on whether or not the plants are equipped with $DeNO_x$.

All Danish MSW incineration plants are equipped with dioxin abatement. The abatement measures for dioxin also contribute to reduce the emission of mercury. Most plants use addition of activated charcoal, a few plants uses addition of coke.

A complete list of flue gas cleaning systems for the Danish waste incineration plants as of 2006 is elaborated by NERI in cooperation with FORCE, see Appendix 2. Only the plants included in this project are included, i.e. plants producing electricity. The information refers to Affaldsinfo.dk (2009), the annual environmental reports for the plants for 2006, the plant websites and personal correspondence with relevant contact persons on several of the plants.

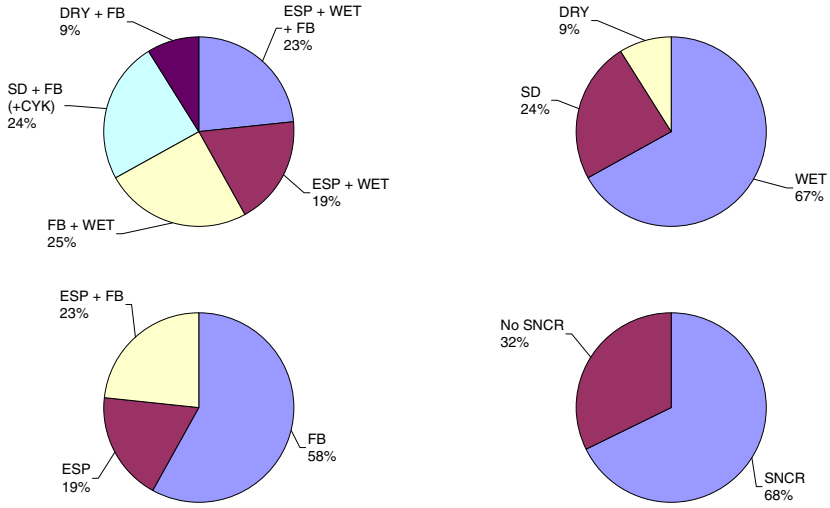
In the energy survey provided by the DEA for 2006 four waste incineration plants with an electricity capacity over 25 MW are listed: Maabjergværket, Horsens Kraftvarmeværk, Sønderborg Kraftvarmeværk and Amagerforbrænding. However, the capacity of each MSW incineration unit in the plants does not exceed 25 MW_e and therefore the plants are included in this project.

In 2006 33 700 TJ of waste were used for CHP production. The fuel consumption divided on flue-gas-cleaning technologies is shown in Figure 3.1.

The majority (67 %) of the waste was incinerated at plants equipped with wet desulphurisation. The share of waste incinerated at plants with semi-dry and dry desulphurisation is considerable with 24 % and 9 %, respectively.

More than half of the waste was incinerated at plants equipped with only a filter bag for particle abatement. The remaining part of the waste was incinerated in plants with only an electrostatic precipitator or with both electrostatic precipitator and filter bag, see Figure 3.1.

In 2006 68 % of the incinerated waste was incinerated at plants equipped with $DeNO_x$ (SNCR).



ESP: Electrostatic precipitator.
FB: Filter bag.
CYK: Cyclone.
WET: Wet desulphurisation.
SD: Semi-dry desulphurisation.
DRY: Dry desulphurisation.

Figure 3.1 Waste consumption divided on types of flue gas cleaning, 2006.

3.2 Straw

In 2006 12 wholly or partially straw fired CHP plants were operating in Denmark.

The following plants are not included in this project as they are above the limit of 25 MW_e: Studstrupværket 3 and 4, Avedøreværket 2, Enstedværket B3 and Amagerværket. Maabjergværket is included since the biomass boiler is below 25 MW_e.

Thisted is included under waste incineration plants since the consumption of waste is greater than the consumption of straw. Grenå is not included because it is a fluid-bed boiler combusting both coal and straw, and thus the emission characteristics deviate considerably from the other plants included in this category. Additionally it is not possible to assign the emissions to the specific fuels.

The six straw fired plants included in this project are shown in Table 3.1. Five of the plants are equipped with a filter bag and the sixth has an electrostatic precipitator. Because of the small number of straw fired plants no subdivision of this category has been made in determining the emission factors. The six plants combusted a total of 2 600 TJ straw in 2006.

Table 3.1 List of straw fired plants.

Plant name	Unit name	MW_e	Fuel	Straw	Flue gas cleaning
Maribo-Sakskøbing Kraftvarmeværk	MSKV 81	11.3	Straw	100 %	FB
Rudkøbing Kraftvarmeværk	QRU Rudkøbing KV	2.3	Straw	100 %	FB
Haslev Kraftvarmeværk	HAV	5	Straw	100 %	FB
Slagelse Kraftvarmeværk	SLV	12[1)]	Straw	100 %	ESP
Masnedøværket	MAV12	9	Straw and wood	94 %	FB
Maabjergværket A/S	MBV	28[2)]	Straw and wood	52 %[3)]	FB

1. Includes production based on steam from a waste incineration plant close by.
2. Includes capacity of waste incineration boiler.
3. For the biomass boiler.

3.3 Wood

In 2006 15[5] wholly or partially wood fired CHP plants were operating in Denmark.

The following plants are not included because they are above 25 MW_e: Avedøreværket 2, Enstedværket B3, Amagerværket, Herningværket, Østkraft and Energi Randers. Maabjergværket is included since the biomass boiler is below 25 MW_e.

Grenå is not included because it is a fluid bed boiler combusting coal, straw and other biomass, which makes it deviate significantly in emission characteristics from the other plants included in this category. Additionally it is not possible to assign the emissions to a specific fuel.

The seven wood fired plants included in this project are shown in Table 3.2. These plants combusted 3 500 TJ wood[6] in 2006. The plants are equipped with either filter bag, electrostatic precipitator (ESP) or a wet scrubber. More than 80 % of the fuel consumption occurred at plants with ESP. Due to the low number of wood fired plants no subdivision has been made for this plant technology when estimating emission factors.

[5] Including a single gas engine using biomass producer gas based on wood.
[6] Wood pellets, wood chips and wood waste.

Table 3.2 List of wood fired plants.

Plant name	Unit name	MW_e	Fuel	Wood	Flue gas cleaning
Assens Fjernvarme Amba	Blok II	4.68	Wood	100 %	ESP
Hjordkær Fjernvarmeværk	Kraftvarmeanlæg	0.6	Wood	100 %	Scrubber
Masnedøværket	MAV12	9	Straw, wood and gas oil	6 %	FB
Maabjergværket A/S	MBV	28[1)]	Straw and wood	48 %[3)]	FB
Novopan Træindustri A/S	Kraft V	5	Wood	100 %	ESP
Køge Kraftvarmeværk	KKV7 +KKV8	26	Wood and fuel oil	98 %	ESP
Dalum Papir A/S	Kedel 3+4 and Turbine 1+2	11[2)]	Natural gas, wood and gas oil	1 %	

[1)] Includes two waste incinerators.
[2)] Includes a natural gas boiler.
[3)] For the biomass boiler.

3.4 Natural gas powered engines

The natural gas powered engines are subdivided based on the make and model of the engine. The subdivision is shown in Table 3.3 together with the different engines share of the natural gas consumption. The total natural gas consumption in engines in 2006 was 28 000 TJ.

The engines are all equipped with oxidation catalysts for reducing the emission of CO. In 2006 approximately 60-65 % of the natural gas was combusted in pre-combustion chamber engines. The group "Other" primarily covers smaller engines including engines below 120 kW_e, which is not covered by the legislative emission limit values (DEPA, 2005).

Table 3.3 Natural gas powered engines divided by make and model, 2006.

Engine make	Model	Open chamber or pre-combustion chamber engine	Natural gas consumption, 2006
Caterpillar	3500	Open chamber	14 %
Caterpillar	3600	Pre-combustion chamber	10 %
Caterpillar	GM34	Pre-combustion chamber	2 %
Deutz	604/620	Open chamber	3 %
Jenbacher	300	Open chamber	15 %
Jenbacher	400	Open chamber	2 %
Jenbacher	600	Pre-combustion chamber	8 %
MAN	Rollo	Open chamber	2 %
Niigata	All	Pre-combustion chamber	0.1 %
Rolls-Royce	K	Pre-combustion chamber	23 %
Rolls-Royce	B	Pre-combustion chamber	1.3 %
Wärtsilä	25SG	Pre-combustion chamber	5 %
Wärtsilä	34SG	Pre-combustion chamber	8 %
Wärtsilä	Other	Pre-combustion chamber	5 %
Waukesha	All	Pre-combustion chamber Open chamber	0.9 %
Cummins	All	Pre-combustion chamber/ Open chamber	0.2 %
Other		-	3 %

Source: DGC, 2009.

3.5 Biogas powered engines

The biogas powered engines are subdivided based on the make and model of the engine. The subdivision is shown in Table 3.4 together with the different engines share of the biogas consumption. The total biogas consumption in engines in 2006 was 3 100 TJ.

Due to a limited number of emission measurements some of the groups have been aggregated when calculating emission factors. The grouping used in calculating emission factors is shown in Table 3.5.

The engines used three different types of biogas: manure based biogas, landfill based biogas and wastewater treatment biogas. The distribution of consumption between the three gas types is shown in Figure 3.2. Most biogas in Denmark is based on manure.

Table 3.4 Biogas powered engines divided by make and model, 2006.

Engine make	Model	Biogas consumption, 2006
Caterpillar	3500	7 %
Caterpillar	3400	0.1 %
Jenbacher	300	32 %
Jenbacher	400	6 %
Jenbacher	200	10 %
Jenbacher	150	0.3 %
Deutz/MWM	616	3 %
Deutz/MWM	232	3 %
Deutz/MWM	234	1.1 %
Deutz/MWM	4408	1.0 %
Deutz/MWM	2016	0.6 %
Deutz/MWM	Other	3 %
Deutz/MWM	469	0.8 %
Rolls-Royce	K	10 %
Waukesha		0.7 %
MAN	2842	10 %
Totem		0.4 %
Valmet		0.2 %
Peugeot		0.01 %
Fiat		0.2 %
MTU		1.1 %
Unknown		8 %

Source: DGC, 2009.

Table 3.5 List of engines used for calculation of emission factors, 2006.

Engine make	Biogas consumption 2006
Jenbacher	49 %
Deutz/MWM	13 %
Rolls-Royce	10 %
MAN 2842	10 %
Other	18 %

Source: DGC, 2009.

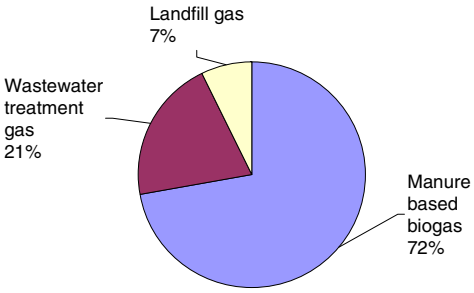


Figure 3.2 Biogas consumption based on origin of the biogas (DGC, 2009).

3.6 Natural gas powered gas turbines

A large share of the gas turbines installed in Denmark is larger than 25 MW_e and is therefore not included in this project.

The natural gas powered turbines are subdivided based on the make and model of the gas turbine. The subdivision is shown in Table 3.6 together with the share of natural gas consumption. The total natural gas consumption for this plant type in 2006 was 6 900 TJ. 7 % of the consumption is on combined cycle plants (DGC, 2009).

Almost all the gas turbines are equipped with low-NO_x burners. One plant is equipped with SCR.

Table 3.6 Natural gas powered turbines, 2006.

Turbine make	Model	Gas consumption
Allison	All	2 %
Alstom/ABB	All	11 %
EGT	Typhoon	53 %
EGT	Tornado	26 %
Solar Mars[1)]	Mars	3 %
Solar Centaur[1)]	Centaur	5 %

[1)] In calculating emission factors Solar Mars and Solar Centaur has been aggregated.
Source: DGC, 2009.

3.7 Oil

3.7.1 Gas oil

CHP plants < 25 MW_e using gas oil can be subdivided into the following categories:

- Combustion engines solely using gas oil (approximately 28 TJ)
- Combustion engines of the dual-fuel type (approximately 36 TJ)
- Gas turbines (approximately 30 TJ)
- Boilers and steam turbines where oil is a small part of the total fuel consumption. The gas oil consumption in this category is larger than for the other categories.

The total consumption of gas oil on plants below 25 MW_e was approximately 163 TJ in 2006 of which 106 TJ was in non-centralised power plants.

3.7.2 Fuel oil

The consumption of fuel oil on plants below 25 MW_e was 2310 TJ in 2006. The majority of the fuel oil consumption is in industrial steam turbine plants. The consumption on two sugar plants and a producer of edible oils account for more than 90 % of the fuel consumption in 2006.

3.8 Biomass producer gas

There is a very low consumption of biomass producer gas in gas engines. In 2006 only two plants were in operation: BioSynergi Castor and Harboøre Varmeværk. The total fuel consumption in 2006 was according to the DEA 88 TJ of wood. The engines consumption of biomass producer gas was 66 TJ.

Several new plants are in operation now and it is expected that the amount of biomass producer gas is increasing. The new plants are mentioned in project report 2 (Jørgensen et al., 2010a).

4 Number of measurements and degree of coverage

In Table 4.1 shows the number of plants (waste incineration line, boiler, turbine or engine) with available emission data. Repeated measurements on the same plant are only counted as one measurement. Data for degree of coverage is included in Appendix 12. By degree of coverage is meant the share of fuel consumption represented by plants where emission measurements are available for this project.

For waste incineration plants 93 measurement reports have been available representing 18 waste incineration lines[7]. Some of the measurement results are below the detection limit. The degree of coverage for most metals is close to 60 % and in general the degree of coverage is higher than 30 %. For measurements of POPs the degree of coverage is lower.

For straw fired plants there were six measurements available, where two were project measurements. These data represented three out of the six plants. In order to strengthen the basis for estimating emission factors it was decided to include data from a previous project, see Chapter 5.4. These data includes measurements for all six straw fired plants. By including the measurements from the previous project 16 data sets are available covering all six plants. The degree of coverage for straw fired plants is 100 % for CO and between 35 % and 85 % for the other pollutants covered.

For wood fired plants only two data sets were available, but similar to straw, measurements from the previous project have been included, see Chapter 5.5. By including the previous measurements there are six data sets for wood fired plants covering two plants. The degree of coverage for wood fired plants is between 31 % and 42 % for the pollutants covered.

For natural gas engines data is available from 157 engines[8]. This results in a degree of coverage for NO_x, UHC and CO of 38 %, while the degree of coverage for several other pollutants, which have only been measured in this project, is as low as 4 %.

For biogas engines data is available form 10 engines. Measurements of special compounds are only done at a single plant. The degree of coverage is 8 % for NO_x, UHC and CO, while for most other pollutants it is approximately 3 %.

[7] One measurement is based on flue gas for several waste incineration lines. This has been calculated as one line.
[8] For the years 2007-2009. In addition is measurement data from 368 engines for the years 2003-2006.

For natural gas turbines data was available from seven gas turbines[9]. The degree of coverage is 31 % for NO_x and CO, and lower for the other included pollutants.

For gas oil powered engines data was available for 17 engines. The degree of coverage for NO_x and CO is 73 %. None of the other pollutants has a degree of coverage of less than 27 %.

Data were available for a single gas oil powered turbine and for two fuel oil powered steam turbines. Data for both engines using biomass producer gas were available.

[9] For the years 2007-2009. In addition is measurement data from 22 turbines for the years 2003-2006.

Table 4.1 Number of plants (engine, turbine, boiler or incineration line) with measurements.

	Unit	Natural gas, engine[1]	Biogas, engine	Natural gas, gas turbine[1]	Gas oil, engine	Gas oil, gas turbine	Fuel oil, steam turbine	Biomass producer gas, engine	Waste	Straw[2]	Wood[2]
SO_2	g per GJ	-	-	-	-	-	-	-	7	5	2
NO_x	g per GJ	157	10	7	17	1	2	2	8	5	2
UHC	g per GJ	157	10	5	12	-	1	2	9	4	2
NMVOC	g per GJ	157	10	5	-	-	-	2	9	4	2
CH_4	g per GJ	157	10	5	12	-	1	2	9	4	2
CO	g per GJ	157	10	7	17	1	2	2	11	6	2
N_2O	g per GJ	10	-	3	2	-	1	1	3	3	1
NH_3	g per GJ	-	-	-	-	-	-	-	13	-	-
TSP	g per GJ	-	-	-	-	-	1	-	12	5	2
As	mg per GJ	2	1	-	1	-	-	1	18	-	-
Cd	mg per GJ	2	1	-	1	-	-	1	18	4	2
Co	mg per GJ	2	1	-	1	-	-	1	18	-	-
Cr	mg per GJ	2	1	-	1	-	-	1	18	-	-
Cu	mg per GJ	2	1	-	1	-	-	1	18	-	-
Hg	mg per GJ	2	1	-	1	-	-	1	18	4	2
Mn	mg per GJ	2	1	-	1	-	-	1	18	-	-
Ni	mg per GJ	2	1	-	1	-	-	1	18	-	-
Pb	mg per GJ	2	1	-	1	-	-	1	18	-	-
Sb	mg per GJ	2	1	-	1	-	-	1	18	-	-
Se	mg per GJ	2	1	-	1	-	-	1	9	-	-
Sn	mg per GJ	-	-	-	-	-	-	-	1	-	-
Tl	mg per GJ	2	1	-	1	-	-	1	18	-	-
V	mg per GJ	2	1	-	1	-	-	1	18	-	-
Zn	mg per GJ	2	1	-	1	-	-	1	9	2	1
PCDD/-F	ng per GJ	2	1	-	1	-	-	1	18	5	2
PBDD/-F	ng per GJ	-	1	-	-	-	-	1	2	-	-
PAH (BaP)	µg per GJ	2	1	-	1	-	-	1	8	3	2
ΣPAH	µg per GJ	2	1	-	1	-	-	1	8	2	2
Naphthalene	µg per GJ	2	1	-	1	-	-	1	3	3	2
HCB	µg per GJ	-	1	-	1	-	-	1	3	2	-
PCB	ng per GJ	-	1	-	1	-	-	1	3	-	-
Formaldehyde	g per GJ	11	3	-	2	-	1	1	-	-	-
Acetaldehyde	g per GJ	4	3	-	2	-	1	1	-	-	-
Acrolein	g per GJ	4	3	-	2	-	1	1	-	-	-
Propanal	g per GJ	4	3	-	2	-	1	1	-	-	-
Acetone	g per GJ	4	3	-	2	-	1	1	-	-	-
Butanal	g per GJ	4	3	-	2	-	1	1	-	-	-
Pentanal	g per GJ	4	3	-	2	-	1	1	-	-	-
Hexanal	g per GJ	4	3	-	2	-	1	1	-	-	-
Benzaldehyde	g per GJ	4	3	-	2	-	1	1	-	-	-
Odour	OU per m^3	6	-	-	-	-	-	-	-	-	-
Efficiency	%	144	-	4	-	-	-	-	-	-	-
HCl	g per GJ	-	-	-	-	-	-	-	8	5	-
HF	g per GJ	-	-	-	-	-	-	-	15	-	-

[1)] For the years 2006-2009. In addition to measurement data for the years 2003-2006.
[2)] Including data from Eltra PSO 3141 (Nielsen & Illerup, 2003).

5 Emission factors

5.1 Method

The emission factors calculated are based on both project measurements and existing measurement reports collected during the project.

Emission factors have been calculated for the following plant types:

- Waste incineration plants
- Straw fired plants
- Wood fired plants
- Natural gas fuelled engines
- Biogas fuelled engines
- Natural gas powered gas turbines
- Gas oil powered engines
- Gas oil powered gas turbines
- Fuel oil powered steam turbines
- Biomass producer gas powered engines

For most of the plant types listed above emission factors have been calculated based on sub-categories. Emission factors have been calculated as a function of plant type for each of the following pollutants:

- SO_2
- NO_x
- NMVOC (In some cases UHC, i.e. the sum of NMVOC and CH_4)
- CH_4 (In some cases UHC, i.e. the sum of NMVOC and CH_4)
- CO
- N_2O
- TSP (Total Suspended Particulates)
- Metals (As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Sb, Se, Sn, Tl, V and Zn)
- PCDD/-F (Includes 17 congeners, see Appendix 11)
- PBDD/-F (Includes 15 congeners, see Appendix 11)
- PAH (Polycyclic Aromatic Hydrocarbons). Contains the 15 compounds included in the Danish Guidance on Air Emissions (DEPA 2001). The total emission of PAH is included in the tables as a simple sum of the 15 compounds (ΣPAH) and as benzo(a)pyrene equivalents "PAH (BaP)". See Appendix 11 for a list of the 15 compounds.
- Naphthalene
- HCB
- PCBs (Includes 12 congeners, see Appendix 11)
- Aldehydes (Formaldehyde, acetaldehyde, acrolein, propanal, acetone, butanal, pentanal, hexanal and benzaldehyde)
- HCl
- HF

The emission factors are calculated in terms of units of mass per GJ fuel consumption.

As previously mentioned the calculated emission factors are based on both project measurements and existing measurement reports. The estimates have been based on all available data including measurements from days on which the operation of the plants was unusual. If such an occurrence has significant influence on the total calculated emission factor this will be emphasised in the discussion of the results. An analysis of the influence of regular disturbances, e.g. breakage of filter bags or of increased emission during start-ups of the plants has not been performed, since it was beyond the scope of this project.

For all plant types emission factors for full load have been calculated. For natural gas engines emission factors have been calculated including the increased emissions during start up and shut down of the engines.

For some plants multiple measurements have been available, and for these plants a simple average has been calculated prior to further data handling, see equation 5.1.

$$EMF_u = \frac{\sum_{i=1}^{n} EMF_i}{n} \qquad \text{Eq. 5.1}$$

where
EMF_u is the emission factor for the plant u in mg/Nm^3 at the given O_2 percentage
EMF_i is the emission factor for the plant u at the date i, in mg per Nm^3
n is the number of measurements on the plant

The emission factors on plant level are converted to units of mass per GJ (E.g. g per GJ). The emission factors are converted from mg/Nm^3 at a specific O_2 percentage to g per GJ using equation 5.2.

$$EMF_{g/GJ} = \frac{EMF_{mg/Nm3} \cdot k_{fuel} \cdot 21}{21 - O_2} \qquad \text{Eq. 5.2}$$

where
$EMF_{mg/nm3}$ is the emission factor in mg/Nm^3
O_2 is the oxygen percentage that the emission factor in mg/Nm^3 is listed at
k_{fuel} is a fuel specific constant in the unit 1000 Nm^3 per GJ
$EMF_{g/GJ}$ is the emission factor in g per GJ

The fuel specific constant k_{fuel} is shown for the relevant fuels in Table 5.1.

Table 5.1 Fuel specific constant, k_{fuel}.

Fuel	k_{fuel} , 1000 Nm^3 / GJ	Reference
Waste	0.249	Calculation based on 5500 Nm^3 flue gas (11 % O_2) per tonnes waste (Illerup et al., 1999). 10.5 GJ/ton in 2006 (DEA 2009). k_{fuel} = (((21-11) / 21) * 5500) / (10.5 *1000) = 0.249
Straw	0.260	Jakobsen (2003)[2)]
Wood	0.272	Jakobsen (2003) [3)]
Natural gas	0.240	Jørgensen (2009)
Biogas[1)]	0.254	Jørgensen (2009)
Gas oil	0.247	Jørgensen (2009)
Fuel oil	0.255	Jørgensen (2009)
Biomass producer gas	0.283	Jørgensen (2009)

[1)] Energy weighted average for the different types of biogas.

[2)] Based on water content of 45 %.

[3)] Based on water content of 15 %.

For each of the 10 plant types emission factors have been calculated for the whole plant type. The emission factors are weighted according to fuel consumption according to plant specific information provided by the DEA (2007). The emission factors are calculated using equation 5.3.

$$EMF_{tech\_a} = \frac{\sum_{i=1}^{n} EMF_i \cdot Q_i}{\sum_{i=1}^{n} Q_i} \qquad \text{Eq. 5.3}$$

where
EMF_{tech_a} is the emission factor for the plant technology in g per GJ
EMF_i is the emission factor for plant i in g per GJ
Q_i is the fuel consumption for plant i according to information by the DEA. Only the relevant fuel is included, e.g. waste for waste incineration plants, straw consumption for straw fires plants etc.
n is the number of plants, where emission measurement data are available.

Most plant types have been subdivided into groups expected to share emission characteristics. These subgroups include e.g. engine types, turbine manufactures and type of flue gas cleaning. Emission factors for the subgroups are calculated using equation 5.4.

$$EMF_{sgr} = \frac{\sum_{i=1}^{n} EMF_i \cdot Q_i}{\sum_{i=1}^{n} Q_i} \qquad \text{Eq. 5.4}$$

where
EMF_{sgr} is the emission factor for the subgroup in g per GJ.
EMF_i is the emission factor for plant i in the subgroup in g per GJ.
n is the number of plants in the subgroup, where measurement data exists.
Q_i is the fuel consumption for plant i in GJ according to DEA (2007). Only the relevant fuel is included.

In addition to the overall calculation procedure (equation 5.3) the total emission factors have also been calculated based on the emission factors of the subgroup. This method is applied when the subdivision of the plants is relevant for the emission of a given pollutant. E.g. the NO_x

emission factor for waste incineration is calculated based on the emission factor for plants with and without $DeNO_x$, respectively. This ensures that the emission factor is not underestimated if plants with $DeNO_x$ are over-represented in the data set.

The final emission factors are calculated based on the subgroups when this is believed to be relevant for the pollutant in question. Calculation of the emission factors of the overall plant type based on the emission factors of the subgroups is done using equation 5.5.

$$EMF_{tech\_b} = \frac{\sum_{i=1}^{n} EMF_{sgr\_i} \cdot Q_{sgr\_i}}{\sum_{i=1}^{n} Q_{sgr\_i}} \qquad \text{Eq. 5.5}$$

where
EMF_{tech_b} is the emission factor for the plant technology b in g per GJ.
EMF_{sgr_i} is the emission factor for the subgroup i in g per GJ.
n is the number of subgroups for which emission factors have been calculated.
Q_{sgr_i} is the fuel consumption of subgroup i according to the DEA (2007). Only the relevant fuel is included.

An overview of the emission factors for the different plant types is shown in Table 5.17 in Chapter 5.13. Chapter 5.3 to Chapter 5.12 below contains a discussion of the emission factors for the different plant types.

5.2 Emission measurements below the detection limit

Some emission measurements have resulted in values below the detection limit. This is especially the case for measurements of heavy metals, PAH and POPs. Such values need to be considered carefully in connection with calculation of emission factors since the result only indicates an emission level between zero and the detection limit.

The emission factors calculated in this project are based on the use of the detection limit in cases where the measurement result is below the detection limit. Another solution could have been to use half the detection limit. The previous project reported in 2003 (Nielsen & Illerup, 2003) used the detection limit in the calculation of the emission factors. In order to ensure consistency for the emission factor time-series the same approach has been applied in this project. This approach is also consistent with how NERI is handling data reported as less than a certain value when elaborating the national emission inventories.

For waste incineration the emission factors have also been calculated by using half the detection limit and by replacing all measurements below the detection limit with zero. This results in a range for the emission factors. This is especially relevant for pollutants with a considerable part of data sets below the detection limit. In the following chapters this will be included in the discussion where relevant.

5.3 Waste incineration plants

Emission factors for waste incineration plants are shown in Table 5.2.

Detailed data including minimum and maximum emission factors, the standard deviation, the number of measurements and the degree of coverage are included in Appendix 3. In addition the emission factors have been calculated based on half the detection limit and zero. The emission factors for the year 2000 are also listed for comparative purposes.

In general the emission factors for waste incineration have decreased substantially compared to the previous project carried out in the period 2000-2003. These reductions must be credited executive order no. 162 from 2003 (DEPA, 2003) that has necessitated extensive improvements to the flue gas cleaning. The emission limit values came into force from 2006 for plants that were in operation prior to March 2003, which is the vast majority of waste incineration plants. The emission limit value for dioxin came into force from 2005.

The SO_2 emission factor is calculated to 8.3 g per GJ, which is 66 % lower than the previously used emission factor and significantly below the emission limit value in the executive order (DEPA, 2003)[10].

The NO_x emission factor in 2006 is calculated to 102 g per GJ, which is 17 % lower than the emission factor in the year 2000. This decrease in emission factor is also due to the new emission limit values in the executive order (DEPA, 2003)[11]. Since 2000 a large number of plants have installed $DeNO_x$ in the form of SNCR. In 2006 68 % of the waste was incinerated at plants equipped with SNCR.

The emission factors for UHC (0.68 g per GJ) and CO (3.9 g per GJ) have both decreased significantly since year 2000 by 44 % and 51 %, respectively. The emission factors for NMVOC and CH_4 have been calculated based on a distribution from the IPCC Guidelines (IPCC, 1996).

The calculated N_2O emission factor of 1.2 g per GJ is practically the same as the emission factor calculated in the year 2000. The emission factor is however based on only three measurements of which one is substantially different from the two others.

The emission factor for NH_3 is calculated to 0.29 g per GJ. An emission factor for NH_3 has not previously been estimated but the calculated value is significantly lower than the level indicated in the BREF document (EU Commission, 2006)[12].

The TSP emission factor is calculated to 0.29 g per GJ, which indicates that a significant reduction in TSP emission has occurred in recent years. The 2006 emission factor is 86 % lower than the emission factor in the year 2000. As in the case with SO_2 and NO_x the reduction must be attributed to the changes to the flue gas cleaning systems at the plants due to the executive order.

The heavy metal emission factors are between 37 % and 96 % lower in 2006 compared to the year 2000. The large decrease of the emission fac-

[10] The emission limit value for SO_2 is 25 g per GJ.
[11] The emission limit value for NO_x is 105 g per GJ for plants with a capacity of more than 6 tonnes waste per hour and 210 g per GJ for plants with a capacity below 6 tonnes waste per hour and that were in operation prior to 2003.
[12] < 10 mg per Nm^3 at 11 % O_2, equivalent to 5 g per GJ.

tors for heavy metals is a result of the emission limit values that came into force in 2006, which has resulted in renovation of many plants. This project has included emission measurements of selenium and zinc that were not part of the project establishing emission factors for the year 2000, and the previously applied emission factors were not nationally referenced.

A large part of the measurements of heavy metals are below the detection limit. If values below the detection limit are set to zero instead of the detection limit the following intervals are calculated: Cadmium: 0.21-0.44 mg per GJ, mercury: 1.71-1.79 mg per GJ and lead: 5.44-5.52 mg per GJ. For mercury and lead measurements below the detection limit have very limited impact on the aggregated emission factors. For several of the other metals a larger share of measurements is below the detection limit. For tin and thallium all measurements are below the detection limit. Intervals for heavy metal emission factors are included in Appendix 3.

When elaborating time-series for the emission factors it is important to consider the effect of measurements below the detection limit. This issue is further discussed in Chapter 5.14.

The emission factor for PCDD/-F is calculated to 5 ng per GJ. This is a decrease of 97 % since year 2000. The large reduction in the emission factor is a consequence of the emission limit value that entered into force in 2005.[13]. At the time of the last project not all waste incineration plants were equipped with dioxin abatement. The emission factor is, however, also significantly (75 %) lower than the previous emission factor calculated for plants with dioxin abatement. However, this might be a result of the lower detection limit in recent emission measurements. In this project relatively few measurements are below the detection limit. If these values are set to zero instead of the detection limit the estimated emission factor interval is 4.2-5 ng per GJ.

The emission measurements for brominated dioxins and furans (PBDD/-F) are all below the detection limit for all congeners. Therefore it has only been established that the emission factor is between 0 and 6.3 ng per GJ. The detection limit for PBDD/-F was higher than for PCDD/-F, therefore it has not been possible to conclude on the emission of PBDD/-F compared to PCDD/-F.

When using the entire data set for PAH the emission factor has been calculated to 12 µg per GJ (BaP) and 191 µg per GJ (ΣPAH). The PAH emission factor (BaP) in 2006 is twice the emission factor calculated for the year 2000. This is inconsistent considering that a reduced PAH emission would be expected since dioxin abatement also reduces PAH emission (EU Commission, 2006).

The PAH emission factor for the year 2000 was based on five project measurements. In this project there are three measurements carried out within the project and five collected measurements. The five collected measurements were all performed in connection with the incineration of wood treated with creosol known to cause elevated emissions of PAH. The elevated emission level during the incineration of this wood is the

[13] The emission limit value applied unless the plant was decommissioned during 2006.

reason why emission measurements are available and the measurements are therefore not representative for normal operations. The whole data set is shown in Figure 5.1. Plant D does not have dioxin abatement at the time of measurement.

In 1999 approximately 4000 tonnes of impregnated wood was incinerated in Denmark[14] (Affaldsinfo.dk, 2009; DEPA, 2001). Due to the very limited amount, the elevated emission level during incineration of creosol treated wood has not been taken into account. The PAH emission factors have therefore been based on the three measurements carried out within this project. When only basing the emission factor on these three measurements the PAH emission factors are calculated to 2.2 µg per GJ (BaP) and 37 µg per GJ (ΣPAH). This constitutes a reduction of 64 % compared to the emission factor for the year 2000.

The BREF document (EU Commission, 2006) provides a range for hazardous waste of < 50 - <500 µg per GJ (ΣPAH). For municipal waste a value of <5000 µg per GJ (ΣPAH) is provided.

The emission factors expressed as ΣPAH and BaP are not used in the national emission inventory as the reporting obligation to CLRTAP only covers four single PAHs[15].

The emission factor for naphthalene is calculated to 129 µg per GJ, which is 96 % lower than the emission factor for the year 2000. Naphthalene is not included in the pollutants inventoried and reported by NERI.

The emission factor for HCB is based on only three measurements, where one of the measurements is 50 times higher than the other two[16]. The emission factor of 4.3 µg per GJ is therefore highly uncertain. However, the emission factor is significantly lower than the emission factor previously used[17].

The emission factor for PCB is calculated to 0.32 ng per GJ. Many of the single congeners are below the detection limit. The emission factor is a factor 10^6 below the emission factor from the EMEP/EEA Guidebook (EEA, 2009)[18]. In the BREF document (EU Commission, 2006) for waste incineration (hazardous waste) is written: "*The available data show values mostly less than detection limit and ranging from < 1 µg/Nm³ to <2 ng/Nm³.*" For municipal waste an emission level of < 5 µg per GJ is provided. The detection limit for the measurements carried out in this project is much lower than the value provided in the BREF document (0.0003 ng per Nm^3 to 0.001 ng per Nm^3). PCB emissions can be reduced in connection with

[14] In 1999 it is estimated that approximately 4000 tonnes of impregnated wood was incinerated corresponding to 10 % of the total amount of impregnated wood (Affaldsinfo.dk 2009). It is expected that there will be incinerated small amounts of impregnated wood in the future.
[15] Benzo(a)pyrene, benzo(b)flouranthene, benzo(k)flouranthene og indeno(1,2,3-cd)pyrene.
[16] One of the measurements is below the detection limit, however, this does not contribute significantly to the uncertainty since the emission factor is calculated to 4.2 ng per GJ if this one measurement is set to 0.
[17] HCB is reported for the first time in 2009. The emission factor of 95 µg per GJ refers to the EMEP/EEA Guidebook (EEA, 2009).
[18] The low detection limit has been confirmed by Claus Degn, AnalyTech (Degn ,2009).

dioxin abatement (EU Commission, 2006); this combined with the low detection limit is probably why the calculated emission factor is so low.

The emission factor for HCl of 1.1 g per GJ[19] and for HF of 0.14 g per GJ[20] is respectively 74 % and 55 % lower compared to the 2000 emission factors. The decrease in emission factors is due to the changes in the flue gas cleaning necessitated by the Danish implementation of the waste incineration directive (DEPA, 2003).

[19] For non-hazardous waste the BREF document lists an HCl emission factor of 1 - 8 mg per Nm^3, corresponding to 0.5 – 4 g per GJ.
[20] For non-hazardous waste the BREF document lists a HF emission factor of < 1 mg per Nm^3, corresponding to < 0.5 g per GJ.

Table 5.2 Emission factors for waste incineration plants, 2006

	Unit		Emission factor
SO_2	g per GJ	<	8.3
NO_x	g per GJ		102
UHC	g per GJ	<	0.68
NMVOC [6)]	g per GJ	<	0.56
CH_4 [6)]	g per GJ	<	0.34
CO	g per GJ	<	3.9
N_2O	g per GJ		1.2
NH_3	g per GJ	<	0.29
TSP	g per GJ	<	0.29
As	mg per GJ	<	0.59
Cd	mg per GJ	<	0.44
Co	mg per GJ	<	0.56
Cr	mg per GJ	<	1.56
Cu	mg per GJ	<	1.30
Hg	mg per GJ	<	1.79
Mn	mg per GJ	<	2.14
Ni	mg per GJ	<	2.06
Pb	mg per GJ	<	5.52
Sb	mg per GJ	<	1.14
Se	mg per GJ	<	1.11
Sn [2)]	mg per GJ	<	1.05
Tl [3)]	mg per GJ	<	0.45
V	mg per GJ	<	0.33
Zn	mg per GJ		2.33
PCDD/-F [7)]	ng per GJ	<	5.0
PBDD/-F [1)]	ng per GJ	<	6.3
PAH (BaP) [8)]	µg per GJ	<	2.2
ΣPAH [8)]	µg per GJ	<	37
Naphthalene[4)]	µg per GJ	<	129
HCB [5)]	µg per GJ	<	4.3
PCB	ng per GJ	<	0.32
HCl	g per GJ	<	1.1
HF	g per GJ	<	0.14

[1)] All measurements are below the detection limit. The emission factor has been calculated between 0 and 6 ng per GJ.
[2)] Based on a single measurement, which is below the detection limit. The emission factor is therefore in the range of 0-1.05 mg per GJ.
[3)] The emission factor is based on a large number of measurements. However, all are below the detection limit. The emission factor is therefore in the range of 0-0.45 mg per GJ.
[4)] Based on three measurements below the detection limit. The emission factor is therefore in the range of 0-129 µg per GJ.
[5)] Based on three measurements. One measurement is 50 times higher than the other two.
[6)] Based on the UHC emission factor and a distribution key based on the IPCC Guidelines (IPCC, 1996).
[7)] If measurements below the detection limit are set to zero a range for the emission factor is calculated to 4.2-5.0 ng per GJ.
[8)] If measurements below the detection limit are set to zero the range for the emission factors are calculated to 0.5-2.2 2 µg per GJ for PAH (BaP) and 28-37 µg per GJ for ΣPAH.

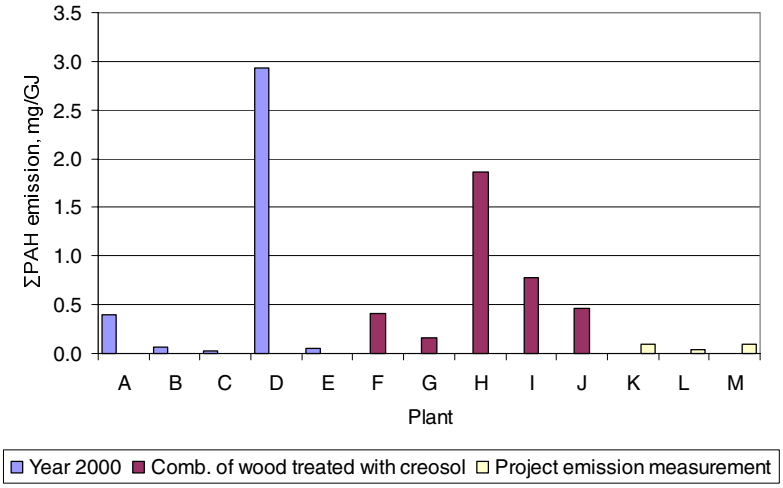


Figure 5.1 ΣPAH emissions from waste incineration plants. The data set is comprised of: 1) measurements carried out previously to establish emission factors for the year 2000 (plant D does not have dioxin abatement) 2) measurements collected within this project (all in connection with incineration of cresol treated wood) and 3) measurements carried out in this project.

In Table 5.3, 5.4 and 5.5 emission factors are shown both for the waste incineration plants as a whole and divided by different types of flue gas cleaning. Detailed data are available in Appendix 3.

For particulate matter, heavy metals, SO_2, HCl and HF it is relevant to calculate emission factors for the different kind of desulphurisation and particle abatement technologies. For both particulate matter and heavy metals there are some unexpected results. For instance from Table 5.3 it can be seen that the emission factors for plants with wet desulphurisation and electrostatic precipitator are lower than plants with an additional filter bag.

The unexpected results for the different types of flue gas cleaning are caused by the fact that the emission level of particulate matter and heavy metals fluctuate significantly for the same plant. This is illustrated in Figure 5.2 that shows repeated measurements of TSP and lead on six different plants. Small variations in waste composition and/or plant operation can seemingly cause large fluctuations in emission level. Since the emission level for a single plant can fluctuate significantly it is important that the emission factors are based on a large number of measurements.

When preparing their annual environmental reports waste incineration plants use TSP emission data from their AMS system for the entire year, while emissions of heavy metals are based on performance measurements. With the operation pattern illustrated in Figure 5.2, the emissions of heavy metals provided by the plants in the environmental accounts must be considered highly uncertain.

The NO_x emission factor for waste incineration is 134 g per GJ for plants without NO_x abatement and 86 g per GJ for plants with NO_x abatement. Emission measurements from plants equipped with SNCR are overrepresented in the data set. The calculated emission factors for other groupings than with/without NO_x abatement are therefore underestimated.

The N_2O emission factor is higher for plants with NO_x abatement. This is expected since the N_2O emission is known to increase when SNCR is in-

stalled. The increase is most significant if urea is applied (Hulgaard, 1991).

The calculated NH_3 emission factor for plants equipped with SNCR is lower than for plants without SNCR. It is not possible to detect a slip of ammonia from the SNCR. It has not been possible to detect a lower NH_3 emission from plants with wet desulphurisation as indicated in the BREF document.

Table 5.3 Emission factors for waste incineration for different flue gas cleaning technologies.

	Unit		EMF based on plant type as a whole		EMF based on type of flue gas cleaning		ESP + WET + FB		ESP + WET		WET + FB		SD + FB (+CYK)		DRY + FB
Fuel consumption, 2006	TJ		33 728		33 728		7911		6244		8379		8191		3003
SO_2	g per GJ	<	9.8	<	**8.3**	<	16.9		-		0.6	<	7.8		-
NO_x	g per GJ		89		95		102		-		92		81		121
UHC	g per GJ	<	**0.68**	<	0.77	<	0.93	<	0.41	<	1.05	<	0.49	<	1.05
NMVOC	g per GJ	<	**0.56**	<	0.64	<	0.77	<	0.34	<	0.87	<	0.41	<	0.87
CH_4	g per GJ	<	**0.34**	<	0.38	<	0.46	<	0.20	<	0.52	<	0.25	<	0.52
CO	g per GJ	<	**3.9**	<	5.5		3.4	<	1.0		6.5	<	4.1		21.3
N_2O	g per GJ		1.4		1.3		2.8		0.4		-		0.5		-
NH_3	g per GJ	<	**0.29**	<	0.26	<	0.83	<	0.01	<	0.06	<	0.12		0.25
TSP	g per GJ	<	0.27	<	**0.29**	<	0.23	<	0.05		0.57	<	0.33	<	0.05
As	mg per GJ	<	0.68	<	**0.59**	<	0.78	<	0.33	<	0.37	<	0.85	<	0.58
Cd	mg per GJ	<	0.50	<	**0.44**	<	0.46	<	0.25	<	0.58	<	0.58	<	0.01
Co	mg per GJ	<	0.70	<	**0.56**	<	0.90	<	0.38	<	0.24	<	0.75	<	0.47
Cr	mg per GJ	<	1.39	<	**1.56**	<	1.22	<	0.41	<	4.05	<	0.65		0.36
Cu	mg per GJ	<	1.12	<	**1.30**	<	0.96	<	0.79	<	2.69	<	0.96	<	0.29
Hg	mg per GJ	<	1.21	<	**1.79**	<	0.51	<	0.99	<	0.52	<	3.95		4.45
Mn	mg per GJ	<	4.19	<	**2.14**	<	1.96	<	0.32	<	1.03	<	5.58	<	0.16
Ni	mg per GJ	<	1.38	<	**2.06**	<	1.51	<	0.45	<	1.91	<	1.00	<	10.08
Pb	mg per GJ	<	3.43	<	**5.52**	<	1.00	<	0.75	<	16.55		2.87	<	3.78
Sb	mg per GJ	<	0.93	<	**1.14**	<	0.63	<	0.23	<	1.49	<	1.30	<	2.94
Se	mg per GJ	<	2.00	<	**1.11**	<	0.27	<	0.16	<	0.52	<	3.44	<	0.52
Sn	mg per GJ	<	1.05	<	**1.05**		-		-		-	<	1.05		-
Tl	mg per GJ	<	0.48	<	**0.45**	<	0.52	<	0.35	<	0.25	<	0.61	<	0.52
V	mg per GJ	<	0.40	<	**0.33**	<	0.49	<	0.28	<	0.07	<	0.55	<	0.13
Zn	mg per GJ		3.91		**2.33**		0.85		1.03		1.55		6.36		0.18
PCDD/-F	ng per GJ	<	4.3	<	**5.0**	<	2.4	<	3.5		10.8	<	4.1		0.8
PBDD/-F	ng per GJ	<	**6**	<	6	<	6		-		-	<	7		-
PAH (BaP)	µg per GJ	<	**2.2**	<	2.2	<	2.4	<	1.9		-	<	2.3		-
ΣPAH	µg per GJ	<	**37**	<	41	<	47	<	21		-	<	49		-
Naphthalene	µg per GJ	<	**129**	<	121	<	110	<	162		-	<	100		-
HCB	µg per GJ	<	**4.3**	<	3.1	<	0.2		10.5		-	<	0.2		-
PCBs	ng per GJ	<	**0.32**	<	0.21	<	0.10	<	0.50		-	<	0.09		-
HCl	g per GJ	<	1.5	<	**1.14**	<	1.62	<	0.92	<	0.32	<	1.68		-
HF	g per GJ	<	0.1	<	**0.14**	<	0.21	<	0.09	<	0.05	<	0.19	<	0.13

Bold indicates the final emission factor used in the national emission inventory.

Table 5.4 Emission factors for waste incineration depending on $DeNO_x$.

	Unit	With $DeNO_x$ (SNCR)	Without $DeNO_x$ (SNCR)	EMF based on NO_x-grouping.
NO_x	g per GJ	86	134	**102**
NH_3	g per GJ	< 0.27	< 0.43	< 0.32
N_2O	g per GJ	1.61	0.51	**1.23**

Table 5.5 Emission factors for waste incineration depending on type of desulphurisation.

	Unit	Wet	Semi-dry	Dry	EMF based on grouping.
HCl	g per GJ	< 1.2	< 1.7	-	< 1.4
HF	g per GJ	< 0.15	< 0.19	< 0.13	< 0.16
SO_2	g per GJ	< 12	< 8	-	< 11

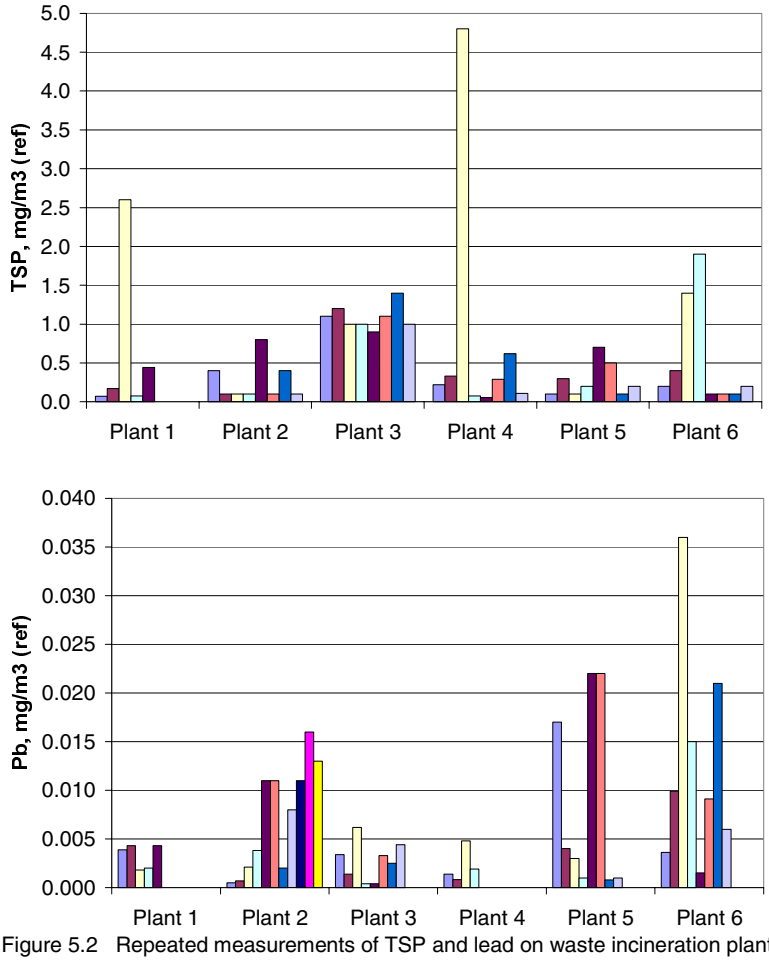


Figure 5.2 Repeated measurements of TSP and lead on waste incineration plants.

5.4 Straw

Emission factors for straw fired CHP plants < 25 MW_e are shown in Table 5.3.

Detailed data including minimum, maximum, standard deviation, number of measurements and degree of coverage are included in Appendix 4. The emission factors for year 2000 are also shown for comparative purposes.

For straw fired plants the available data in this survey has been limited since only three of the six plants were covered by project measurements or collected data. All pollutants are not included in all three available measurement reports. This means that the data set is smaller than the data set used to establish the emission factors for year 2000. Due to the small number of straw fired plants, this plant type has not been divided in to subtypes.

Straw fired plants have not been affected by new legislative demands since the previous project reported in 2003 (Nielsen & Illerup, 2003). Therefore the emission measurements from the previous emission survey have been included. The old data has been discarded if the emission measurements were below the detection limit and a new measurement with lower detection limit is available in this project. Only pollutants covered by project measurements have been updated.

The resulting changes in emission factors are considered as improved emission factors for the period 2000 onwards. There is no basis to conclude that there has been any change in the overall emission characteristics for the plant type. The data included to calculate the emission factors covers the period 2000-2008.

Emissions from straw fired plants are generally less stabile than for other fuel types. This is caused by significant changes in the properties of the straw. The emission characteristics vary significantly depending on water content, alkali content and amount of ashes. The emission factors for straw fired plants are therefore more uncertain than other fuels that have a more stable quality.

For SO_2 the emission factor of 49 g per GJ is almost identical to the emission factor calculated for year 2000 (47 g per GJ). This is also the case for NO_x where the calculated emission factor of 125 g per GJ is only slightly lower than the emission factor for year 2000 (131 g per GJ).

The emission factor for UHC is calculated to 0.94 g per GJ, which is almost identical to the previous emission factor of 0.93 g per GJ. Only one out of the seven available measurements is above the detection limit. For CO the calculated emission factor of 67 g per GJ is very close to the emission factor previously used of 63 g per GJ.

The N_2O emission factor has been calculated to 1.1 g per GJ, which is 20 % lower than the emission factor established for year 2000. The measurements upon which the previous emission factors were based are generally all slightly higher compared to the new measurements. It has not been possible to clearly explain this apparent reduction. It can not be ruled out that it is due to a change in measurement technique. Since there are no available explanations for the apparent decrease in emission factor, it has been decided to include both the new measurements and the previous measurements in calculating the emission factor. All measurements - both new and old - are above the detection limit. The calculated emission factor is slightly lower than the IPCC default range of 1.5-15 g per GJ (IPCC, 1996).

The emission factor for TSP of 2.3 g per GJ is 42 % lower than the emission factor calculated for the year 2000. Since no technological changes of

the plants have occurred since year 2000 it has been decided to include the emission measurements available from the previous emission factor survey. For one plant the previous project only included one rather high measurement whereas this project includes two new measurements that both shows lower emission level. These new measurements contribute to lower the total emission factor. It has been checked that all three measurements are within the normal emission range for the plant. However the variability of the TSP emission from single straw fired plants is considerable. For some larger straw fired plants the variation of the TSP emission through a year is shown in Figure 5.3, which is from a report elaborated by DONG Energy (Wolff & Hansen, 2007).

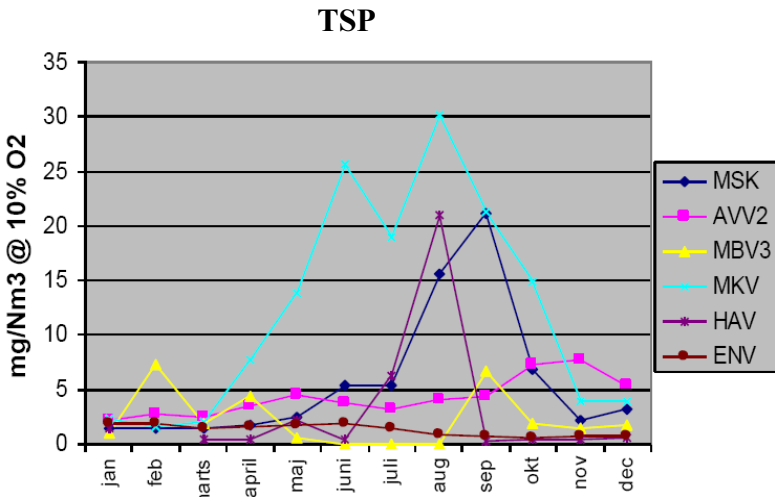


Figure 5.3 Time-series for the TSP emission from larger straw fired plants (Wolff & Hansen, 2007).

The emission factors for cadmium (0.32 mg per GJ) and mercury (0.31 mg per GJ) are 60 % and 49 % lower, respectively, than the emission factors for year 2000. Both the old and new emission factors are based on the detection limit, since all measurements have been below the detection limit. The old data has been discarded where new data for the same plant has been available, due to a lower detection limit for the new measurements. For the three plants where new data is not available, the old data from 2000 is included. The calculated emission factors are in good agreement with the EMEP/EEA Guidebook[21] (EEA, 2009), which for biomass lists an emission factor range for cadmium of 0.1-3 mg per GJ and an emission factor range for mercury of 0.4-1.5 mg per GJ. For zinc an emission factor of 0.41 mg per GJ has been calculated. This emission factor is slightly lower than the emission factor range provided in the Guidebook of 1-150 mg per GJ.

The emission factor for PCDD/-F is calculated to 19 ng I-Teq per GJ, which is 12 % lower than the emission factor for 2000.

For PAH the old emission measurements appears to be at a higher level compared to this project. However, due to the very limited number of measurements there are not basis to conclude a trend in the emission factor, therefore both old and new data are applied. The emission factor for PAH (BaP) is calculated to 0.12 mg per GJ and the emission factor for

[21] Tier 1 approach for source category 1A4a/c, biomass

ΣPAH is calculated to 5.9 mg per GJ, which is 19 % lower than the emission factor for the year 2000.

The emission factor for naphthalene is calculated to 12 mg per GJ, which is 20 % lower than the emission factor for 2000.

For HCl the emission factor has been calculated to 56 g per GJ, which is 21 % higher than the emission factor for 2000. The emission factor for HCB is calculated to 0.11 µg per GJ. This is lower than the emission factor range of 3-9 µg per GJ provided in the EMEP/EEA Guidebook[22] (EEA, 2009).

Table 5.3 Emission factors for straw fired plants, 2006.

	Unit	Emission factor
SO_2	g per GJ	49
NO_x	g per GJ	125
UHC (C)[1)]	g per GJ	< 0.94
NMVOC	g per GJ	< 0.78
CH_4	g per GJ	< 0.47
CO	g per GJ	67
N_2O	g per GJ	1.1
TSP	g per GJ	< 2.3
Cd [2)]	mg per GJ	< 0.32
Hg [2)]	mg per GJ	< 0.31
Zn	mg per GJ	0.41
PCDD/-F	ng per GJ	< 19
PAH (BaP)	µg per GJ	< 125
ΣPAH	µg per GJ	< 5946
Naphthalene	µg per GJ	12088
HCB	µg per GJ	< 0.11
HCl	g per GJ	56

[1)] Only one of seven measurements is above the detection limit.
[2)] All measurements are below the detection limit.

5.5 Wood

Emission factors for wood fired plants < 25 MW_e are shown in Table 5.4.

Detailed data including minimum, maximum, standard deviation, number of measurements and degree of coverage are included in Appendix 5. The emission factors for year 2000 are shown for comparative purposes.

The data available for wood fired plants is very limited. Only two out of seven plants have been covered by project measurements or collected measurement reports. Not all relevant pollutants are included in the two available measurements. On the other hand only four of the seven plants are relevant in calculating an emission factor for wood fired plants, since the three other plants have a very low share of wood in the overall fuel consumption. The emission factor calculated will be used for the wood consumption for the three plants.

Since the previous emission factor survey in 2000-2003 (Nielsen & Illerup, 2003) there has not been any new legislative demands for this plant type.

[22] Tier 1 approach for emission source category 1A4a/c, biomass.

Due to the limited number of new measurements available, the measurement reports from the previous survey have been included. Old values below the detection limit have been discarded if the new data available has a lower detection limit. Only emission factors for pollutants covered by the project measurement have been updated. Four out of six available data sets are from the old emission factor survey. Due to the limited data available there has not been made any subdivisions of this plant type.

The changes observed in the emission factors are considered to be improved emission factors valid from 2000 onwards, since the available data can not support a conclusion of a change in emission characteristics from this plant type.

An emission factor for SO_2 has been calculated to 1.9 g per GJ, which is close to the previously applied emission factor of 1.74 g per GJ. The NO_x emission factor has been calculated to 81 g per GJ, which is 18 % higher than the emission factor previously used.

The emission factor for UHC of 6.1 g per GJ is 53 % higher than the previously used emission factor. Two of the three measurements are below the detection limit. For CO the emission factor is calculated to 90 g per GJ, which is 14 % higher than the previously used emission factor.

For N_2O the emission factor has been calculated to 0.8 g per GJ, which is identical to the previously used value.

The emission factor for TSP is calculated to 10 g per GJ, which is 26 % higher compared to the previously used emission factor.

The emission factor for cadmium of 0.27 mg per GJ is 70 % lower compared to the previous emission factor. The large reduction is due to a significantly lower detection limit in the new project measurement compared to the measurements carried out in 2000-2002. The emission factor may still be overestimated because a measurement with a high detection limit is still used for another plant in calculating the emission factor. The emission factor is within the emission factor range provided by the EMEP/EEA Guidebook[23] (EEA, 2009) of 0.1-3 mg per GJ.

The emission factor for mercury is calculated to 0.40 mg per GJ, which is 44 % lower than the previously used emission factor. All measurements are below the detection limit, but in the new project measurement the detection limit is significantly lower than in the previous survey.

The zinc emission factor is calculated to 2.3 mg per GJ. Zinc was not included in the previous project. The new emission factor is in agreement with the emission factor range of 1-150 mg per GJ in the EMEP/EEA Guidebook (EEA, 2009). The calculated emission factor is significantly lower than the emission factor previously used in the Danish emission inventory of 136 mg per GJ.

For PCDD/-F the emission factor is calculated to 14 ng per GJ, which is 14 times higher than the previously used emission factor. The measurement carried out in this project showed an emission level that was 30

[23] Tier 1 approach for emission source category 1A4a/c, biomass.

times a previous emission measurement carried out at the same plant, and it is this difference that affects the total emission factor. The new emission factor is still below the range of 30-500 ng per GJ in the EMEP/EEA Guidebook (EEA, 2009).

The emission factor for PAH (BaP) is calculated to 13 µg per GJ, which is 65 % higher than the previous emission factor. The emission factor for naphthalene is 12 % higher than the previous emission factor.

Table 5.4 Emission factors for wood fired plants, 2006.

	Unit	Emission factor
SO_2	g per GJ	< 1.9
NO_x	g per GJ	81
UHC (C) [1)]	g per GJ	< 6.1
NMVOC	g per GJ	< 5.1
CH_4	g per GJ	< 3.1
CO	g per GJ	90
N_2O	g per GJ	0.8
TSP	g per GJ	10
Cd	mg per GJ	0.27
Hg [2)]	mg per GJ	< 0.40
Zn	mg per GJ	2.3
PCDD/-F	ng per GJ	< 14
PAH (BaP)	µg per GJ	< 13
ΣPAH	µg per GJ	< 664
Naphthalene	µg per GJ	2314

[1)] Two of three measurements are below the detection limit.
[2)] All measurements are below the detection limit.

5.6 Natural gas powered engines

All gas engines are smaller than 25 MW_e and are therefore within the scope of this project.

Emission factors for gas engines are calculated for both the period 2003-2006 and for 2007 onwards. This distinction is made because new emission limit values entered in to force from 2007[24] (DEPA, 2005). To comply with the new emission limit values most engines have been adjusted and/or retrofitted with oxidation catalysts to reduce CO emission. The emission factors for 2007 onwards are presented in Table 5.5. Detailed data including minimum, maximum, standard deviation and number of engines with measurements are included in Appendix 6. Emission factors for the period 2003-2006 are shown in Chapter 5.14.

Only few measurements include CH_4 and NMVOC, therefore the emission factors for these pollutants are based on a distribution for total UHC calculated by DGC. This distribution is based on nine measurements and is further described in project report no. 4 (Jørgensen et al., 2010b).

In addition to full load emission factors emission factors including the elevated emission contribution during start-up and shut-down of the engines has been calculated. The emission factors for NO_x, UHC (CH_4 and

[24] Executive order no. 621: Engines installed prior to October 17 1998 (The majority of Danish gas engines) must adhere to the emission limit values no later than October 17 2006.

NMVOC) and CO have been adjusted for start-up and shut-down. These factors are presented in Table 5.5. The adjustment of the emission factors is based on correction factors calculated in a previous project (Nielsen et al., 2008).

The emission factors for NO_x, UHC, CO, N_2O, odour and electrical efficiency are based on emission factors for the single engine types. The emission factors for aldehydes are based on emission factors for engines with and without specific reduction measures for aldehydes. The emission factors for TSP, heavy metals, PCDD/-F, PAH and naphthalene are due to the limited number of measurements available, not subdivided but calculated for all natural gas engines as a whole.

No emission measurements are available for the group of engines designated "Other". These engines account for 3 % of the natural gas consumption in natural gas engines. Some of the engines in this category are smaller engines that are not covered by the executive order no. 621; therefore these could potentially have emission factors that deviated significantly from the other engine types. However, due to the limited fuel consumption it is not believed that this issue would have any considerable effect on the total emission factors.

The full load emission factor for NO_x (135 g per GJ) is 20 % lower than the emission factor calculated for the year 2000. The decrease in emission factor can be attributed to executive order no. 621 and the resulting modifications performed on the engines to adhere to the emission limit values. Adjusted for start-up and shut-down the emission factor is unchanged at 135 g per GJ. The previously applied emission factor for the period after the implementation of executive order n. 621 was 148 g per GJ (Nielsen et al., 2008). The emission factor has therefore been lowered by 9 %.

For UHC the full load emission factor has been calculated to 421 g per GJ, which is 13 % lower compared to the emission factor calculated for 2000. This is again a consequence of the engine modifications brought on by executive order no. 621. The oxidation catalysts installed to reduce CO emissions do not have a significant impact on the UHC emission. Adjusted for start-up and shut-down, the UHC emission factor is 435 g per GJ. The previously used emission factor for the period after the implementation of executive order n. 621 was 434 g per GJ (Nielsen et al., 2008). The emission factor is therefore practically unchanged.

The NMVOC emission factor has decreased more than the CH_4 emission factor. The full load emission factor for NMVOC of 89 g per GJ is 24 % lower than the emission factor for 2000, while the full load emission factor for CH_4 of 466 g per GJ is 10 % lower compared to the emission factor for 2000. The adjusted emission factors taking start-up and shut-down into account are 92 g per GJ for NMVOC and 481 g per GJ for CH_4. This constitutes a decrease of 13 % for the NMVOC emission factor and an increase of 4 % of the CH_4 emission factor compared to the previously used emission factor for the period after implementation of executive order no. 621.

The full load emission factor for CO is calculated to 56 g per GJ, which is 68 % lower compared to the emission factor for the year 2000. The large

reduction is due to the installation of oxidation catalysts that have been necessitated to adhere to the emission limit values set out in executive order no. 621. When adjusting for start-up and shut-down the emission factor is 58 g per GJ. This is 49 % lower than the emission factor previously used for the period after implementation of executive order no. 621.

For N_2O the emission factor calculated of 0.6 g per GJ is 56 % lower than the emission factor calculated for the year 2000. This emission factor is still higher than the default provided in the IPCC Guidelines (IPCC, 2006), which is 0.1 g per GJ (0.03-0.3 g per GJ). Instinctively an increase of the N_2O emission factor would be expected due to the increased use of oxidation catalysts. However, since it is not possible to rule out that the change in emission level is due to changes in measurement technique, the new emission factor will be used for the entire time-series. The basis for calculating the N_2O emission factor is better in this project than in the previous project.

Emission factors for 14 metals have been calculated. NERI has not previously estimated emissions of metals from gas fired plants. The EMEP/EEA Guidebook (EEA, 2009) includes emission factors for nine metals. The emission factor calculated for selenium of 0.20 mg per GJ is above the range provided in the Guidebook[25]. However, both measurements are under the detection limit and NERI will therefore use the emission factor provided in the EMEP/EEA Guidebook of 0.01 mg per GJ. The emission factors calculated for arsenic and mercury[26] are in agreement with the EMEP/EEA Guidebook (EEA, 2009) while the emission factors calculated for cadmium, chromium, cobber, nickel, lead and zinc are lower than the ranges provided in the Guidebook. Measurements of tin and thallium are below the detection limit but these pollutants are neither covered by the national inventory nor by the EMEP/EEA Guidebook.

The emission factor for PCDD/-F is calculated to 0.57 ng I-Teq per GJ. The emission factor is based on measurements from two engines and only two congeners (1,2,3,4,6,7,8-HeptaCDD & OCDD) were above the detection limit. If the remaining congeners are set to zero instead of the detection limit a range for the emission factor of 0.006 to 0.57 ng I-Teq per GJ is established. The emission factor based on the detection limit is in good agreement with the EMEP/EEA Guidebook (EEA, 2009), which provides a general PCDD/-F emission factor for natural gas of 0.5 ng I-Teq per GJ.

The emission factor for PAH (BaP) is calculated to 13 µg per GJ, which is 44 % lower than the emission factor calculated for the year 2000 (23 µg per GJ). The emission factor is based on two measurements where a large number of the single PAH compounds are below the detection limit. If measurements below the detection limit are set to zero an interval of 10-13 µg per GJ is calculated, therefore the measurements below the detection limit do not greatly influence the total emission factor. ΣPAH has

[25] According to the EMEP/EEA Guidebook (EEA, 2009) the emission factor is between 0.004 and 0.03 mg per GJ.
[26] Both mercury measurements are below the detection limit but the calculated emission factor is identical to the emission factor in the EMEP/EEA Guidebook.

been calculated to 1025 µg per GJ. If measurements below the detection limit are set to zero an interval of 1020-1025 µg per GJ is calculated.

For naphthalene the emission factor has been calculated to 2 452 µg per GJ, which is 69 % lower than the emission factor calculated for the year 2000. The new emission factor is based on measurements on two engines, while the emission factor for 2000 was based on three measurements.

The emission factors for aldehydes are generally lower (29-94 %) than the emission factors for 2000. However, the emission factor for acetone is twice as high as for the year 2000. The installation of oxidation catalysts to reduce CO emissions also seems to have had a positive effect on the emissions of aldehydes, even though previous studies have shown this not to be the case. However, the data foundation is still insufficient to draw firm conclusions regarding the reduction of aldehyde emissions in connection with oxidation catalysts for CO reduction (Jørgensen et al., 2010b).

The odour emission measured in this project of 3 904 OU per m^3 is significantly lower compared to the previous study. Odour emission measurements are highly uncertain.

The electrical efficiency has been calculated to 39.6 % (Lower calorific value), which is 1.3 %-point higher compared to year 2000.

DGC has previously calculated a SO_2 emission factor of 0.5 g per GJ for natural gas (Kristensen, 2003).

Table 5.5 Full load emission factors for natural gas engines, 2007.

	Unit	Emission factor
NO_x	g per GJ	135
UHC	g per GJ	421
NMVOC [2)]	g per GJ	89
CH_4 [2)]	g per GJ	466
CO	g per GJ	56
N_2O	g per GJ	0.6
As	mg per GJ	< 0.05
Cd	mg per GJ	< 0.003
Co	mg per GJ	< 0.20
Cr	mg per GJ	0.05
Cu	mg per GJ	0.01
Hg	mg per GJ	< 0.10
Mn	mg per GJ	< 0.05
Ni	mg per GJ	0.05
Pb	mg per GJ	0.04
Sb	mg per GJ	< 0.05
Se [1)]	mg per GJ	< 0.20 (0.01)
Tl	mg per GJ	< 0.20
V	mg per GJ	< 0.05
Zn	mg per GJ	2.91
PCDD/-F [3)]	ng per GJ	< 0.57
PAH (BaP) [4)]	µg per GJ	< 13
ΣPAH [4)]	µg per GJ	< 1025
Naphthalene	µg per GJ	2452
Formaldehyde [5)]	g per GJ	14.1
Acetaldehyde [5)]	g per GJ	1.01
Acrolein [5)]	g per GJ	0.016
Propanal [5)]	g per GJ	0.078
Acetone [5)]	g per GJ	0.45
Butanal [5)]	g per GJ	0.071
Pentanal [5)]	g per GJ	0.012
Hexanal [5)]	g per GJ	0.0063
Benzaldehyde [5)]	g per GJ	0.0019
Odour	OU per m^3	3904
Electrical efficiency	%	39.6

1. Based on two measurements both of which are below the detection limit. Since the resulting emission factor is higher than the interval provided in the EMEP/EEA Guidebook (EEA, 2009) NERI will use the Guidebook emission factor (0.01 mg per GJ).
2. Based on the UHC emission factor and a distribution key established by DGC based on nine measurements.
3. Based on measurements on two engines. Two congeners are detected: 1,2,3,4,6,7,8-HeptaCDD and OctaCDD. If the remaining congeners are set to zero an interval of 0.006 – 0.57 ng I-Teq per GJ is calculated.
4. Based on two measurements. For one of the engines only to PAH compounds are below the detection limit for the other engine 13 PAH compounds are below the detection limit. If the compounds under the detection limit are set to zero the following intervals are calculated: PAH (BaP) – 10-13 µg per GJ and ΣPAH – 1020 – 1025 µg per GJ. The influence of measurements below the detection limit is not of great significance.
5. Based on measurements performed in 2003-2009.

Table 5.6 Emission factors for natural gas engines including start/stop correction, 2007.

	Unit	Full load emission factor	Start/stop correction factor (Nielsen et al., 2008)	Emission factor incl. start/stop
NO_x	g per GJ	135	1.00	135
UHC (C)	g per GJ	421	1.03	435
NMVOC	g per GJ	89	1.03	92
CH_4	g per GJ	466	1.03	481
CO	g per GJ	56	1.05	58

For every engine make and model emission factors for NO_x, UHC, CO and N_2O odour and aldehydes have been calculated together with the electrical efficiency. The data set is not complete for all engine types. The emission factors are shown in Table 5.10 .

The NO_x emission factor is for all engine types below the emission limit value corresponding to 173 g per GJ. The engine types that were previously above the emission limit value have been modified and the differences between engine types have decreased.

As expected the emission factor for UHC is generally higher for pre-combustion chamber engines. One engine make – Niigata – has an emission factor that are higher than the emission limit value. It is due to the fact that the Niigata engines have not been modified to adhere to the emission limit values. Instead they are used for ancillary services/regulating reserves with annual operating hours less than 500. In this case the emission limit values do not apply. Except for the Niigata engines all engines makes that were previously high in emissions have obtained significant reductions.

The CO emission factors have decreased for all engine makes and with the exception of Niigata they are all significantly below the emission limit value corresponding to 157 g per GJ. Oxidation catalysts are installed on all engines.

The N_2O emission factors are similar for all engine types and are generally lower than the 2000 emission factors.

The limited number of odour measurements makes it difficult to conclude anything regarding the odour emission for different engine types. The emission factors for aldehydes are not based on a division between engine types but instead on a subdivision of plants with and without aldehyde reduction. The data set for aldehydes on engine makes/models is based solely on project measurements and is therefore smaller than the data set used for calculating the total emission factor.

Further analysis of the development for the different engine makes/models is available in project report 4 (Jørgensen et al., 2010b).

Table 5.10 Gas engine types fuel consumption, emission factors and efficiency, 2007.

Engine make	Model	Fuel consumption	NO_x	UHC (C)	CO	N_2O	Odour	Formal-dehyde	Acetal-dehyde	Acrolein	Propanal	Acetone	Butanal	Pentanal	Hexanal	Benzal-dehyde	Electri-cal effi-ciency
		TJ	g/GJ	g/GJ	g/GJ	g/GJ	OU/m^3	g/GJ	g/GJ	g/GJ	g/GJ	g/GJ	g/GJ	g/GJ	g/GJ	g/GJ	%
Caterpillar	3500	3805	142	423	41	0.44	5650	0.28	0.001	0.001	0.003	0.006	0.001	0.001	0.001	0.001	37.2
Caterpillar	3600	2723	94	569	57	0.57	-	18.48	-	-	-	-	-	-	-	-	38.7
Caterpillar	GM34	538	123	484	49	0.76	-	-	-	-	-	-	-	-	-	-	43.3
Deutz	604/620	726	143	182	46	0.65	-	-	-	-	-	-	-	-	-	-	34.8
Jenbacher	300	4221	149	352	66	0.67	-	8.28	0.545	0.082	0.047	0.052	0.025	0.069	0.005	0.010	37.7
Jenbacher	400	452	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Jenbacher	600	2203	104	314	34	0.56	7008	7.70	-	-	-	-	-	-	-	-	41.7
MAN	Rollo	538	143	66	137	-	-	-	-	-	-	-	-	-	-	-	33.0
Niigata	All	28	87	1188	161	-	-	-	-	-	-	-	-	-	-	-	37.0
Rolls-Royce	K	6417	159	470	60	0.59	1800	15.02	1.045	0.002	0.051	0.737	0.010	0.010	0.002	0.002	41.6
Rolls-Royce	B	364	139	330	47	0.77	-	-	-	-	-	-	-	-	-	-	45.5
Wärtsilä	25SG	1369	132	372	64	0.63	-	-	-	-	-	-	-	-	-	-	-
Wärtsilä	34SG	2162	111	448	67	0.48	-	14.86	0.774	0.002	0.020	0.107	0.061	0.005	0.002	0.002	42.1
Wärtsilä	Other	1390	125	537	25	-	-	-	-	-	-	-	-	-	-	-	39.2
Waukesha	All	252	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cummins	All	60	157	324	48	-	4150	-	-	-	-	-	-	-	-	-	39.6
Other	All	785	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

5.7 Biogas powered engines

All biogas powered engines are below 25 MW_e and are therefore included in the scope of this project. The engines combust biogas based on animal manure, landfill gas or biogas from wastewater treatment. Biogas based on animal manure is utilised both at larger plants and at smaller plants, e.g. single farm level. The emission factors for biogas fuelled engines are shown in Table 5.7. Detailed data is available in Appendix 7.

Even though biogas engines are also included in executive order no. 621 there has not been distinction between before and after 2006. This is due to the fact that biogas engines in operation prior to 2006 only have to adhere to the new emission limit values from 2013.

Only few measurements include CH_4 and NMVOC. The emission factors for CH_4 and NMVOC are based on a distribution key for total UHC established by DGC. This distribution is established based on three measurements as described in project report 4 (Jørgensen et al., 2010b).

For biogas powered engines only full load emission factors are calculated since the influence of start-up and shut-down has not been mapped.

The emission factors for NO_x, UHC and CO are based on the make and model of the engine. For the remaining pollutants the emission factors are based on all biogas engines as a whole due to the limited data available.

Only data from a single engine is available for emission of metals, PAH, PCDD/-F, PBDD/-F, HCB and PCB. These measurements were carried out on an engine fuelled by biogas produced from a landfill. No data are available regarding these pollutants for animal manure biogas or wastewater treatment biogas. Since 72 % of the biogas consumption is based on animal manure the calculated emission factors are not necessarily representative for the biogas used in Denmark. Because no similar measurements are available for manure based biogas NERI has decided to use the emission factors for metals, PAH, PCDD/-F and HCB[27] derived for landfill gas for all biogas consumption.

The consumption of biogas in engines has increased by 32 % from 2000 to 2006. This increase has primarily taken place for larger engines (> 0.5 MW_e). While the consumption of biogas in engines larger than 0.5 MW_e has increased by 55 % since 2000, the consumption in engines smaller than 0.5 MW_e has only increased by 5 %. Data is shown in Table 5.8. The changed distribution influences the aggregated emission factors.

[27] PBDD/-F and PCB are not part of the national air emission inventory.

The emission factor for SO_2 has not been updated and the currently used emission factor of 19 g per GJ (Nielsen & Illerup, 2003) will continue to be used in the Danish inventory.

For NO_x the emission factor of 202 g per GJ is 63 % lower than the emission factor for the year 2000. Nine measurements are available, which is fewer than in the previous study but the engine types where measurements are available cover 82 % of the biogas consumption. Single farm plants are not represented in the new measurement data neither is Caterpillar engines, which had a remarkably high NO_x emission factor in the previous study. These two circumstances could contribute to the lower emission factor. But because of the low biogas consumption in these plants it is not thought that this is the dominant reason for the lower emission factor. Almost 50 % of the biogas consumption in 2006 was in Jenbacher engines and the emission factor for this engine make has decreased 40 %.

The emission factor for UHC of 333 g per GJ is 31 % higher than the emission factor for the year 2000. For Jenbacher engines, which represent almost half of the biogas consumption in 2006, the emission factor has increased by 15 %. For Deutz/MWM the increase in emission factor is remarkable due to new models (Jørgensen et al., 2010b). The UHC emission is typically greater from larger engines where the biogas consumption has increased the most.

For CO the emission factor is calculated to 310 g per GJ, which is 14 % higher than the emission factor in 2000.

The emission factors for NO_x, UHC and CO are lower than the future emission limit values for engines larger than 1 MW. Several engine types are above the emission limit values in force from 2013.

The emission factor for N_2O is three times higher than the emission factor for 2000. The old emission factor was only based on a single measurement, while the new emission factor is based on three measurements. Therefore the new emission factor will be used for the entire time-series.

For both PCDD/-F and PBDD/-F all congeners were below the detection limit. The PCDD/-F emission factor is calculated to 0.96 ng per GJ and the emission factor for PBDD/-F is calculated to 5 ng per GJ. Neither the previous survey nor the EMEP/EEA Guidebook (EEA, 2009) includes emission factors for PCDD/-F or PBDD/-F for biogas.

The emission factors for metals are shown in Table 5.7. The EMEP/EEA Guidebook (EEA, 2009) does not contain emission factors for metals from biogas. The emission factors are based on a single measurement on an engine using landfill gas. Several of the emission factors are below the detection limit so they may be overestimated.

The PAH (BaP) emission factor of 4.2 µg per GJ is 39 % higher than the emission factor for the year 2000. However, many of the single compounds are below the detection limit. If these are set to zero the estimated interval for the PAH emission factor is 2.1 - 4.2 µg per GJ (BaP). The PAH emission factors for both 2000 and 2006 are based on a single measurement.

For naphthalene the emission factor is 39 % higher than the emission factor for the year 2000. For formaldehyde the emission factor of 8.7 g per GJ is 39 % lower compared to the 2000 emission factor. Some of the aldehydes emission factors are higher and some are lower compared to the emission factors for the year 2000. The data set is limited[28].

The emission factors for HCB and PCB is calculated to 0.19 µg per GJ and < 0.19 ng per GJ, respectively. These emission factors have not previously been measured in Denmark nor are they included in the EMEP/EEA Guidebook (EEA, 2009). All PCB congeners were below the detection limit.

[28] The emission factors for year 2000 are based on seven measurements, and the emission factors for 2006 are based on three measurements.

Table 5.7 Emission factors for biogas engines, 2006.

	Unit	Emission factor
NO_x	g per GJ	202
UHC	g per GJ	333
NMVOC	g per GJ	10
CH_4	g per GJ	434
CO	g per GJ	310
N_2O	g per GJ	1.6
As	mg per GJ	< 0.04
Cd	mg per GJ	0.002
Co	mg per GJ	< 0.21
Cr	mg per GJ	0.18
Cu	mg per GJ	0.31
Hg	mg per GJ	< 0.12
Mn	mg per GJ	0.19
Ni	mg per GJ	0.23
Pb	mg per GJ	0.005
Sb	mg per GJ	0.12
Se	mg per GJ	< 0.21
Tl	mg per GJ	< 0.21
V	mg per GJ	< 0.04
Zn	mg per GJ	3.95
PCDD/-F [1)]	ng per GJ	< 0.96
PBDD/-F	ng per GJ	< 5.0
PAH (BaP) [2)]	µg per GJ	< 4.2
ΣPAH [2)]	µg per GJ	< 606
Naphthalene	µg per GJ	4577
HCB	µg per GJ	0.19
PCB [3)]	ng per GJ	< 0.19
Formaldehyde	g per GJ	8.7
Acetaldehyde	g per GJ	0.116
Acrolein	g per GJ	0.001
Propanal	g per GJ	0.023
Acetone	g per GJ	0.023
Butanal	g per GJ	0.001
Pentanal	g per GJ	0.001
Hexanal	g per GJ	0.001
Benzaldehyde	g per GJ	0.013

[1)] All congeners are below the detection limit.
[2)] Six PAHs are above the detection limit. If the remaining compounds are set to zero the following interval for the emission factors are calculated: PAH (BaP) – 2.1-4.2 µg per GJ and ΣPAH – 581-606 µg per GJ.
[3)] All congeners are below the detection limit.

Table 5.8 Biogas consumption for engines divided by capacity for the years 2000 and 2006.

	Unit	2000	2006	Increase in consumption
Plants larger than 0.5 MW_e	TJ	1 296	2 011	55 %
Plants smaller than 0.5 MW_e	TJ	1 089	1 140	5 %
Total	TJ	2 386	3 151	32 %

Generally, the emission factors for biogas are higher than for the same engines combusting natural gas. This is mainly noticeable for

CO because the biogas engines are not equipped with oxidation catalysts.

Table 5.9 Emission factors for different biogas engine makes.

Engine make	NO_x g per GJ	UHC g per GJ	CO g per GJ
Deutz/MWM	228	525	306
MAN	365	121	228
Jenbacher	161	284	344
Rolls Royce	205	535	240

5.8 Natural gas powered gas turbines

Emission factors for natural gas powered gas turbines < 25 MW_e are shown in Table 5.10. Detailed data is available in Appendix 8.

Emission factors for natural gas powered gas turbines are calculated for the period 2003-2006 and for 2007 onwards. This split is relevant because new emission limit values for gas turbines entered into force in 2007[29] (DEPA, 2005). Emission factors for 2003-2006 are shown in Chapter 5.14. The gas consumption has been decreasing in later years. In 2006 the natural gas consumption in gas engines was only 74 % of the consumption in 2000.

Some gas turbines have been decommissioned in connection with the implementation of the new emission limit values but the majority of the gas turbines that could not adhere to the emission limit values have been equipped with low-NO_x burners (dry low-NO_x burners). A single plant is equipped with SCR.

No measurements include CH_4 and NMVOC. The emission factors of CH_4 and NMVOC are based on a distribution key for UHC, referenced to a previous study (Nielsen & Illerup, 2003).

The national emission factors for NO_x, UHC and CO are based on the emission factors of the subgroups. The N_2O emission factor is based on all gas turbines as a whole.

DGC has previously estimated an emission factor for SO_2 for natural gas of 0.5 g per GJ (Kristensen, 2003). This emission factor will be applied unchanged.

The NO_x emission factor of 48 g per GJ is 62 % lower than the emission factor for the year 2000. This can be attributed to the emission limit value in executive order no. 621 (DEPA, 2005). The emission limit value corresponds to an emission factor of 63 g per GJ. This emission limit value was significantly lower than the earlier legislation and entailed the installation of low-NO_x burners on the vast majority of gas turbines.

[29] Executive order no. 621: Gas turbines installed prior to October 17, 1998 (Most of the Danish gas turbines are installed prior to this date) shall adhere to the emission limit values at October 17 2006.

The UHC emission factor of 2.5 g per GJ is 8 % higher than the emission factor for the year 2000 (2.3 g per GJ). This emission factor is based on data from 2003-2006 because there are no newer measurements available. The emission factor is based on one measurement above the detection limit and on two data sets below the detection limit (Jørgensen et al., 2010b). The previous emission factor was based on measurement data below the detection limit.

The CO emission factor is calculated to 4.8 g per GJ, which is 20 % lower compared to the 2000 emission factor.

For N_2O the emission factor of 1.0 g per GJ is 53 % lower compared to the emission factor for 2000. All three measurements that the emission factor is based on are considerably lower than the emission factor for 2000. The new emission factor is still somewhat higher than the IPCC value (IPCC, 2006)[30].

Table 5.10 Emission factors for natural gas turbines, 2007.

	Unit	Emission factor
NO_x	g per GJ	48
UHC [1)]	g per GJ	2.5
NMVOC [2)]	g per GJ	1.6
CH_4 [2)]	g per GJ	1.7
CO	g per GJ	4.8
N_2O	g per GJ	1.0
Efficiency	%	28.4

[1)] Based on three measurements from 2003-2006.
[2)] Based on a distribution of the UHC factor (Nielsen & Illerup, 2003).

Emission factors for different make/models of gas turbines are shown in Table 5.11. One additional turbine is included in the calculation. However, since only one turbine of this type is installed in Denmark it is not shown in order to ensure the anonymity of the plant. For all turbine makes the NO_x emission factor has decreased since 2000. Approximately 80 % of the natural gas consumption is used in EGT Tornado and EGT Typhoon turbines.

For the Allison turbine the CO emission factor is higher than the emission limit value. The high emission factor is not representative for all Allison turbines but it the result of defective flue gas cleaning equipment that has now been changed (Jørgensen et al., 2010b). The data for Allison is part of the calculation of the total CO emission from gas turbines.

[30] The N_2O emission factor for natural gas powered gas turbines in Energy Industries is listed at 0.1 g per GJ (0.03-0.3 g per GJ).

Table 5.11 Emission factors for gas turbines depending of turbine make, 2007.

Turbine make	NO_x, g/GJ	UHC, g/GJ	CO, g/GJ	Efficiency, %
Allison	36	11.3	86	25.0
EGT, Typhoon	49	2.2	2	27.9
EGT, Tornado	38	-	6	-
Solar	56	-	3	30.2

5.9 Oil

There have been calculated emission factors for gas oil powered engines, gas oil powered turbines and fuel oil powered steam turbines.

Emission factors have not been estimated for gas oil powered steam turbines, since gas oil on the relevant plants only account for a minor share of the total fuel consumption. Nevertheless the gas oil consumption in these plants exceeds the total gas oil consumption in the remaining plants.

All the three measurements carried out within this project were performed in 2007, which means that the plants should adhere to the emission limit values established in executive order no. 621 (DEPA, 2005). The emission limit values only apply for new installations taken in use after 2005 not for plants already in operation.

5.9.1 Gas oil powered engines

The emission factors for gas oil powered engines are shown in Table 5.12. Detailed data are available in Appendix 9. There has not been made any subdivision of the data for gas oil powered engines.

There have not previously been calculated emission factors based on measurements on gas oil powered engines in operation in Denmark.

The NO_x emission factor is calculated to 942 g per GJ, which is very high compared to the other plant types included in this project. The emission factor is higher than the emission factor previously used in the Danish inventory (700 g per GJ).

The emission factor for UHC is calculated to 18 g per GJ based on the project measurements. However, this factor has not been included since there seems to have been a problem with the measurement of NMVOC as discussed below.

The CH_4 emission factor has been calculated to 24 g per GJ, which is remarkably high compared to the IPCC Guidelines (IPCC, 2006). In the IPCC Guidelines an interval of 1 to 10 g per GJ for gas oil in the energy sector is provided as well as a specific emission factor of 4 g per GJ for gas oil powered engines.

In the project measurements it has not been possible to detect any NMVOC emission. This can be caused by the fact that the analysis of the measurement only covered light hydrocarbons, lighter than C_5H_x. In the EMEP/EEA Guidebook (EEA, 2009) an emission factor for NMVOC of 37 g per GJ is listed with an interval of 19 to 56 g per GJ. NERI will use the emission factor of 37 g per GJ in the national emission inventory.

The N_2O emission factor is calculated to 2.1 g per GJ, which is almost identical to the previously used emission factor of 2 g per GJ. The CO emission factor is calculated to 130 g per GJ, which is 30 % higher than the previously used emission factor.

The emission factors for heavy metals are all low compared to both the previously used emission factors and the emission factors listed in the EMEP/EEA Guidebook (EEA, 2009). However, the emission factor for zinc is much higher compared to the same references. The calculated zinc emission factor is also much higher than the emission factors calculated for all other plant types. There is nothing that indicates that there were any abnormalities in the operating conditions during the measurement.

Most of the PAHs were above the detection limit; however, a few compounds were below the detection limit[31]. If the emission of the compounds below the detection limit is set to zero an interval for PAH (BaP) is calculated to 30-33 µg per GJ and an interval for ΣPAH to 8984-8988 µg per GJ. The influence of the few PAH below the detection limit is therefore insignificant.

The emission factor for PCDD/-F is calculated to 0.99 ng per GJ, which is close to the previously used emission factor. Three congeners were above the detection limit: 1,2,3,4,6,7,8-HeptaCDD, OCDD and 1,2,3,4,6,7,8-HeptaCDF. If the remaining congeners are set to zero an interval of 0.014-0.99 ng per GJ is calculated.

All PCBs were below the detection limit and the same was the case for HCB.

[31] Benzo[k]fluoranthene, Benzo[a]pyrene and Dibenz[a,h]anthracene were below the detection limit.

Table 5.12 Emission factors for gas oil powered engines.

	Unit	Emission factor
NO_x	g per GJ	942
UHC (C) [1)]	g per GJ	- (46)
NMVOC [1)]	g per GJ	- (37)
CH_4	g per GJ	24
CO	g per GJ	130
N_2O	g per GJ	2.1
As	mg per GJ	0.06
Cd	mg per GJ	0.01
Co	mg per GJ	0.28
Cr	mg per GJ	0.20
Cu	mg per GJ	0.30
Hg	mg per GJ	0.11
Mn	mg per GJ	0.01
Ni	mg per GJ	0.01
Pb	mg per GJ	0.15
Sb	mg per GJ	0.06
Se	mg per GJ	0.22
Tl	mg per GJ	0.22
V	mg per GJ	0.01
Zn	mg per GJ	58
PCDD/-F [2)]	ng per GJ	0.99
PAH (BaP) [3)]	µg per GJ	33
ΣPAH [3)]	µg per GJ	8988
Naphthalene	µg per GJ	17642
HCB	µg per GJ	0.22
PCB [4)]	ng per GJ	0.13
Formaldehyde	g per GJ	1.3
Acetaldehyde	g per GJ	0.404
Acrolein	g per GJ	0.002
Propanal	g per GJ	0.045
Acetone	g per GJ	0.082
Butanal	g per GJ	0.055
Pentanal	g per GJ	0.007
Hexanal	g per GJ	0.002
Benzaldehyde	g per GJ	0.029

[1)] There was not detected any NMVOC emission. This is probably due to the fact that there was not analysed for heavier hydrocarbons than C_5H_x. The measurements of NMVOC and UHC have therefore been disregarded. The emission factor of 37 g per GJ (EEA, 2009) is used in future inventories. Based on this factor an UHC emission factor of 46 g C per GJ is calculated.
[2)] Three congeners are detected: 1,2,3,4,6,7,8-HeptaCDD, OctaCDD and 1,2,3,4,6,7,8-HeptaCDF. If the remaining congeners are set to zero in stead of the detection limit the emission factor interval will be 0.014 – 0.99 ng I-Teq per GJ.
[3)] Most PAH compounds were measured, but benzo(k)fluoranthene, benzo(a)pyrene and dibenz(a,h)anthracene were below the detection limit. If these are set to zero instead of the detection limit the emission factor interval will be 30 - 33 µg/GJ for PAH (BaP) and 8984 – 8988 µg/GJ ΣPAH. Therefore it does not have significant impact on the total PAH emission that the three compounds were below the detection limit.
[4)] All PCB congeners are below the detection limit.

5.9.2 Gas oil powered gas turbines and fuel oil powered steam turbines

The emission factors for gas oil powered gas turbines and fuel oil powered steam turbines are shown in Table 5.13.

The NO_x emission factor for gas oil powered gas turbines is 76 % lower than the previously used emission factor. The previously used emission factor was based on plant specific data for larger gas turbines collected in 2001. It will be relevant to develop an emission factor time-series.

The NO_x emission factor for fuel oil powered steam turbines is 38 % higher than the previously used emission factor.

Similar to the gas oil powered engines the emission measurements of UHC and NMVOC have been disregarded due to the same issues. NERI will use the emission factor provided by the EMEP/EEA Guidebook (EEA, 2009) of 0.8 g per GJ[32]. The CH_4 emission factor for the fuel oil powered steam turbine plant has been calculated to 1.3 g per GJ. This is lower than the previously used emission factor. DGC has calculated an UHC emission factor of 1.0 g per GJ based on the available emission measurements. In this work an emission factor calculated as the sum of CH_4 and NMVOC is used, i.e. 1.6 g C per GJ.

The N_2O emission factor for the fuel oil powered steam turbine plant is calculated to 5 g per GJ, which is higher than the previously used emission factor of 2 g per GJ. The emission factor is outside the range provided in the IPCC Guidelines of 0.2-2 g per GJ (IPCC, 2006).

All measurements of aldehydes were below the detection limit.

Table 5.13 Emission factors for gas oil powered turbines and fuel oil powered steam turbines.

All factors based on a single measurement	Unit	Emission factor, gas oil powered gas turbine	Emission factor, fuel oil powered steam turbine
NO_x	g per GJ	83	136
UHC (C) [1)]	g per GJ	-	- (1.6)
NMVOC [2)]	g per GJ	-	- (0.8)
CH_4	g per GJ	-	< 1.3
CO	g per GJ	2.6	2.8
N_2O	g per GJ	-	5.0
TSP	g per GJ	-	9.5
Formaldehyde	g per GJ	-	< 0.0020
Acetaldehyde	g per GJ	-	< 0.0012
Acrolein	g per GJ	-	< 0.0012
Propanal	g per GJ	-	< 0.0012
Acetone	g per GJ	-	< 0.0041
Butanal	g per GJ	-	< 0.0012
Pentanal	g per GJ	-	< 0.0012
Hexanal	g per GJ	-	< 0.0012
Benzaldehyde	g per GJ	-	< 0.0012

[1)] Based on the emission measurements an emission factor of 1.0 g per GJ is calculated. Since it is chosen to use the NMVOC emission factor on the EMEP/EEA Guidebook, the UHC emission factor is calculated based on this factor and the CH_4 emission factor.

[32] EMEP/EEA Guidebook (EEA, 2009), source category 1A1a, using heavy fuel oil, Table 3-7 NMVOC 0.8 g/GJ (0.8-1.28 g/GJ)

[2] DGC could not detect an emission of NMVOC. Since the analysis did not cover hydrocarbons heavier than C_5H_x and there is a significant discrepancy compared with the EMEP/EEA Guidebook an emission factor of 0.8 g per GJ (EEA, 2009) is used.

5.10 Biomass producer gas

The emission factors for biomass producer gas are shown in Table 5.14. Detailed data are available in Appendix 10.

There have not previously been estimated emission factors for biomass producer gas in Denmark, but the emission factors can instead be compared to engines using natural gas or biogas.

The NO_x emission factor is at the same level as gas engines fuelled with natural gas or biogas. The emission factor of UHC is much lower and the emission factor of CO much higher than for natural gas or biogas engines. This is due to the composition of the biomass producer gas, since the gas has a high content of CO and H_2 but a low content of hydrocarbons compared to natural gas and biogas[33].

All measurements of PCDD/-F, PBDD/-F and PCB congeners are below the detection limit while the HCB emission factor was calculated to 0.8 µg per GJ.

The PAH (BaP) emission factor is estimated to 4.9 µg per GJ. Only two PAH compounds were above the detection limit, if the remaining are set to zero an interval of 0.07- 4.9 µg per GJ is calculated.

[33] A gas analysis from the plant in Harboøre shows the following contents: 23 %-vol. CO, 19 %-vol. H_2 and 5%-vol. CH_4 (Wit & Jensen, 2009).

Table 5.14 Emission factors for engines combusting biomass producer gas.

	Unit	Emission factor
NO_x	g per GJ	173
UHC	g per GJ	12
NMVOC	g per GJ	2
CH_4	g per GJ	13
CO	g per GJ	586
N_2O	g per GJ	2.7
As	mg per GJ	0.12
Cd	mg per GJ	< 0.009
Co	mg per GJ	< 0.22
Cr	mg per GJ	0.029
Cu	mg per GJ	< 0.045
Hg	mg per GJ	0.54
Mn	mg per GJ	0.008
Ni	mg per GJ	0.014
Pb	mg per GJ	0.022
Sb	mg per GJ	< 0.045
Se	mg per GJ	< 0.18
Tl	mg per GJ	< 0.18
V	mg per GJ	< 0.045
Zn	mg per GJ	0.058
PCDD/-F [1)]	ng per GJ	< 1.7
PBDD/-F [2)]	ng per GJ	< 7.2
PAH (BaP) [3)]	µg per GJ	< 4.9
ΣPAH [3)]	µg per GJ	< 181
Naphthalene	µg per GJ	8492
HCB	µg per GJ	0.80
PCB [4)]	ng per GJ	< 0.24
Formaldehyde	g per GJ	1.5
Acetaldehyde	g per GJ	0.56
Acrolein	g per GJ	< 0.001
Propanal	g per GJ	0.048
Acetone	g per GJ	0.56
Butanal	g per GJ	< 0.001
Pentanal	g per GJ	< 0.001
Hexanal	g per GJ	< 0.001
Benzaldehyde	g per GJ	0.14

[1)] All PCDD/-F congeners are below the detection limit.
[2)] All PBDD/-F congeners are below the detection limit.
[3)] Only fluorene and phenanthrene is measured. The rest of the PAH were below the detection limit. If the PAH not measured are set to zero in stead of the detection limit the following intervals for the emission factors are calculated: PAH (BaP) 0.07-5.1 µg per GJ and ΣPAH 139 - 181 µg per GJ.
[4)] All PCB congeners are below the detection limit.

5.11 Congeners and equivalence factors for PCDD/-F, PBDD/-F, PAH and PCB

The measurement data for single congeners of PCDD/-F, PBDD/-F, PAH and PCB are included in Appendix 11. The toxic equivalence factors used are also included in Appendix 11.

The equivalence factors used for PCDD/-F are based on WHO (1998). The same factors are used in the Danish implementation of the waste incineration directive.

There are no established equivalence factors for PBDD/-F. Therefore the equivalence factors for PCDD/-F have been used. This is in accordance with recommended practice (IPCS-WHO 1998). The substitution of one halogen with another, in this case substituting chlorine with bromine, is not generally believed to change the toxicity significantly (Behnisch et al., 2003; Samara et al., 2009). By using the same toxic equivalence factors it is also possible to evaluate the emission intensity of PBDD/-F compared to PCDD/-F.

The toxic equivalence factors for PCB refer to WHO (2005). PCB is one of the POPs where countries are recommended to report emission to the Convention on Long-Range Transboundary Air Pollution. Due to the toxicity of PCB it has been considered in this project to improve the basis for the emission factor, since the uncertainty of previous studies has proved to be significant (Thomsen et al., 2009).

The sum of PAH is calculated in two ways. One as a simple sum (*∑PAH*) of the 15 PAH compounds that have been analysed for in this project. The other is to express the PAH emission as benzo(a)pyrene equivalents (*PAH (BaP)*). The equivalency factors refer to the Danish Guidance for air pollution (DEPA, 2001). Four PAH compounds are inventoried and reported to the LRTAP Convention. Table 5.15 shows the emission factors for the four compounds.

Table 5.15 Emission factors for the four PAH compounds included in the national inventory.

	Unit	Gas oil	Biomass producer gas	Biogas	Natural gas	Waste	Straw	Wood
		Engine	Engine	Engine	Engine			
Benzo[b/j]fluoranthene	µg per GJ	15	< 2.0	< 1.2	< 9	< 1.7	< 0.5	< 15[1)]
Benzo[k]fluoranthene	µg per GJ	< 1.7	< 2.0	< 1.2	< 1.7	< 0.9	< 0.5	< 5[1)]
Benzo[a]pyrene	µg per GJ	< 1.9	< 2.0	< 1.3	< 1.2	< 0.8	< 0.5	< 11[1)]
Indeno[123-cd]pyrene	µg per GJ	1.5	< 2.0	< 0.6	< 1.8	< 1.1	< 0.5	< 10[1)]

[1)] One of the two measurements from a wood fired plant was above the detection limit

5.12 Emission factors for particulate matter

In parallel to this a separate project has measured emissions of particulate matter with specific emphasis on fine and ultrafine particles. The project (PSO project commissioned by Energinet.dk) was carried out by FORCE Technology and the title was "Characterization of ultrafine particles from CHP Plants < 30 MW_e" (Energinet.dk, 2009).

In the project measurements of fine and ultrafine particles from six plants were made. The measurements were made at the same plants and at the same time as the project measurements in this project. When analysing the results it became clear that there was

problems with the consistency of TSP measurements and the measurements of fine and ultrafine particles. For some plants a higher emission of $PM_{2.5}$ and PM_1 was measured than the TSP measurement. The results are shown in Table 5.16. The table shows that the TSP measurement is lower than the $PM_{2.5}$ or PM_1 measurement for one of the waste incineration plants and for all three biomass fired plants. The different results for the TSP measurement and the fine and ultrafine particles emission are due to different measurement techniques. Because of the conflicting results it has been decided not to include the data from the PM project when calculating emission factors. The data are presented in this report for information purposes.

Table 5.16 Emission factors for particulate matter.

Plant type	Unit	O_2 , %	$PM_{0.1}$	PM_1	$PM_{2.5}$	TSP
Waste, plant A2 (ESP+WET)	mg/Nm^3 (ref)	11	0.0008	0.060	0.065	0.070
Waste, plant A3 (SD+FB (+CYK))	mg/Nm^3 (ref)	11	0.0001	1.287	2.360	1.600
Waste, plant A1 (ESP+WET+FB)	mg/Nm^3 (ref)	11	0.000003	0.0001	0.0021	0.004
Straw, plant B1	mg/Nm^3 (ref)	10	0.049	3.3	-	0.030
Straw, plant B2	mg/Nm^3 (ref)	10	0.0031	0.86	-	0.030
Wood, plant B3	mg/Nm^3 (ref)	10	0.073	4.5	6.116	0.900
Natural gas, engine	mg/Nm^3 (ref)	5	0.0640	0.352	-	-
Natural gas, engine during start-up	mg/Nm^3 (ref)	5	0.0544	1.856	-	-
Biogas (Landfill), engine	mg/Nm^3 (ref)	5	0.0032	0.064	0.112	-
Gas oil	mg/Nm^3 (ref)	5	0.0800	0.928	1.024	-

Data for fine and ultrafine particles refer to Energinet.dk (2009).

5.13 Emission factors, comparison of plant types

The emission factors for decentralised CHP production in 2006 (2007 for natural gas) are shown in Table 5.17. In Appendix 1 the emission factors are shown in units of mass per m_n^3 flue gas.

Waste incineration plants have the highest emission factors for all metals with the exception of zinc, HCB and PCB. PCB emission has only been measured above the detection limit for waste incineration plants, for all other plant types all PCB congeners were below the detection limit.

Straw fired plants have the highest emission factors of SO_2, PCDD/-F, PAH (BaP) and HCl. Wood fired plants have the highest emission factor for particulate matter (TSP).

Natural gas engines have the highest emission factors of UHC, NMVOC and CH_4. The emission factors of several aldehydes are also the highest.

Emission factors for both biogas engines and natural gas turbines are generally low for all measured pollutants.

Oil powered engines have the highest emission factor of NO_x, zinc, naphthalene and ΣPAH. Fuel oil powered steam turbines have the highest emission factor of N_2O.

The CO emission factor is the highest for engines combusting biomass producer gas.

The emission factors for PBDD/-F are all based on measurements below the detection limit for all congeners; it is therefore irrelevant to compare the emission factors across plant types.

Table 5.17 Overview of emission factors for decentralised CHP production, 2006/2007.

	Unit	Natural gas, engine	Biogas, engine	Natural gas, gas turbine	Gas oil, engine	Gas oil, gas turbine	Fuel oil, steam turbine	Biomass producer gas, engine	Waste	Straw	Wood
SO_2	g per GJ	-	-	-	-	-	-	-	< 8.3	49	< 1.9
NO_x	g per GJ	135[8)]	202	48	942	83	136	173	102	125	81
UHC (C)	g per GJ	435[8)]	333	2.5[9)]	(46) [10)]	-	(1.6) [10)]	12	< 0.68	< 0.94[5)]	< 6.1[6)]
NMVOC	g per GJ	92[4) 8)]	10[4)]	1.6[4)]	(37)[10)]	-	(0.8) [10)]	2.3[4)]	< 0.56[4)]	< 0.78[4)]	< 5.1[4)]
CH_4	g per GJ	481[4) 8)]	434[4)]	1.7[4)]	24	-	< 1.3	13[4)]	< 0.34[4)]	< 0.47[4)]	< 3.1[4)]
CO	g per GJ	58[8)]	310	4.8	130	2.6	2.8	586	< 3.9	67	90
N_2O	g per GJ	0.58	1.6	1.0	2.1	-	5.0	2.7	1.2	1.1	0.83
NH_3	g per GJ	-	-	-	-	-	-	-	< 0.29	-	-
TSP	g per GJ	-	-	-	-	-	9.5	-	< 0.29	< 2.3	10
As	mg per GJ	< 0.045	< 0.042	-	< 0.055	-	-	0.116	< 0.59	-	-
Cd	mg per GJ	< 0.003	0.002	-	< 0.011	-	-	< 0.009	< 0.44	< 0.32[3)]	0.27
Co	mg per GJ	< 0.20	< 0.21	-	< 0.28	-	-	< 0.22	< 0.56	-	-
Cr	mg per GJ	0.048	0.18	-	0.20	-	-	0.029	< 1.6	-	-
Cu	mg per GJ	0.015	0.31	-	0.30	-	-	< 0.045	< 1.3	-	-
Hg	mg per GJ	< 0.098[3)]	< 0.12	-	< 0.11	-	-	0.54	< 1.8	< 0.31[3)]	< 0.40[3)]
Mn	mg per GJ	< 0.046	0.19	-	0.009	-	-	0.008	< 2.1	-	-
Ni	mg per GJ	0.045	0.23	-	0.013	-	-	0.014	< 2.1	-	-
Pb	mg per GJ	0.043	0.005	-	0.15	-	-	0.022	< 5.5	-	-
Sb	mg per GJ	< 0.049[3)]	0.12	-	< 0.055	-	-	< 0.045	< 1.1	-	-
Se	mg per GJ	(0.01)[7)]	< 0.21	-	< 0.22	-	-	< 0.18	< 1.1	-	-
Sn	mg per GJ	-	-	-	-	-	-	-	< 1.0[2)]	-	-
Tl	mg per GJ	< 0.20[3)]	< 0.21	-	< 0.22	-	-	< 0.18	< 0.45[3)]	-	-
V	mg per GJ	< 0.048	< 0.042	-	0.007	-	-	< 0.045	< 0.33	-	-
Zn	mg per GJ	2.9	4.0	-	58	-	-	0.058	2.3	0.41	2.3
PCDD/-F	ng per GJ	< 0.57	< 0.96[1)]	-	< 0.99	-	-	< 1.7[1)]	< 5.0	< 19	< 14
PBDD/-F	ng per GJ	-	< 5.0[1)]	-	-	-	-	< 7.2[1)]	< 6.3[1)]	-	-
PAH (BaP)	µg per GJ	< 13	< 4.2	-	< 33	-	-	< 4.9	< 2	< 125	< 13
ΣPAH	µg per GJ	< 1025	< 606	-	< 8988	-	-	< 181	< 37	< 5946	< 664
Naphthalene	µg per GJ	2452	4577	-	17642	-	-	8492	< 129[3)]	12088	2314
HCB	µg per GJ	-	0.19	-	< 0.22	-	-	0.80	< 4.3	< 0.11	-
PCB	ng per GJ	-	< 0.19[1)]	-	< 0.13[1)]	-	-	< 0.24[1)]	< 0.32	-	-
Formaldehyde	g per GJ	14.1	8.7	-	1.3	-	< 0.002	1.5	-	-	-
Acetaldehyde	g per GJ	1.01	0.12	-	0.40	-	< 0.001	0.56	-	-	-
Acrolein	g per GJ	0.016	0.001	-	< 0.002	-	< 0.001	< 0.001	-	-	-
Propanal	g per GJ	0.078	0.023	-	0.045	-	< 0.001	0.048	-	-	-
Acetone	g per GJ	0.45	0.023	-	< 0.082	-	< 0.004	0.56	-	-	-
Butanal	g per GJ	0.071	0.001	-	0.055	-	< 0.001	< 0.001	-	-	-
Pentanal	g per GJ	0.012	0.001	-	< 0.007	-	< 0.001	< 0.001	-	-	-
Hexanal	g per GJ	0.0063	0.001	-	< 0.002	-	< 0.001	< 0.001	-	-	-
Benzaldehyde	g per GJ	0.0019	0.013	-	< 0.029	-	< 0.001	0.14	-	-	-
Odour	OU per m^3	3904	-	-	-	-	-	-	-	-	-
Efficiency	%	39.6	-	28.4	-	-	-	-	-	-	-
HCl	g per GJ	-	-	-	-	-	-	-	< 1.14	56	-
HF	g per GJ	-	-	-	-	-	-	-	< 0.14	-	-

[1)] The measurements were below the detection limit for all congeners.
[2)] Based on a single measurement below the detection limit.
[3)] All measurements were below the detection limit.
[4)] Based on a distribution key for UHC.
[5)] Only one of seven measurements was above the detection limit.
[6)] Two of three measurements were below the detection limit.

[7] Two measurements were made and both were below the detection limit. The calculated emission factor has been disregarded and instead an emission factor of 0.01 mg per GJ (EEA, 2009).
[8] Increased emissions during start-up and shut-down included.
[9] Based on data from 2003-2006.
[10] The project measurements have been disregarded and instead the NMVOC emission factor from the EMEP/EEA Guidebook is used. The UHC emission factor is calculated based on the emission factors of CH_4 and NMVOC.

5.14 Emission factors 2000 - 2006

NERI annually reports national emission inventories for the years X-2 back to the base year of the relevant protocols. For greenhouse gases the base year is 1990. SO_2 is reported back to 1980, NO_x, NMVOC, CO and NH_3 are reported back to 1985, heavy metals and POPs are reported back to 1990 and emissions of particulate matter are reported back to the year 2000. This requirement means that NERI has to maintain emission factor time-series for the pollutants where reporting requirements exist. The following pollutants are covered by the reporting requirements: SO_2, NO_x, NMVOC, CH_4, CO, CO_2, N_2O, NH_3, TSP, As, Cd, Cr, Cu, Hg, Ni, Pb, Se, Zn, PCDD/-F, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, indeno(1,2,3-cd)pyrene and HCB.

The emission factors calculated in this project for 2006 or 2007 have been used to develop time-series where possible. In the following sections the assumptions made to construct the time-series are described and discussed. Furthermore emission factors for natural gas engines and gas turbines for the years 2003-2006 calculated in this project are presented.

5.14.1 Waste incineration plants

New emission limit values came into force for waste incineration plants in 2006. The emission limit value for dioxin was for the majority of plants already in force from 2005. Modifications of the plants are assumed to have taken place over several years prior to 2006; therefore a linear reduction of emission factors has been assumed between 2003 and 2006. After 2006 it has been assumed that the emission factors have been constant. For dioxin a linear reduction has been assumed from 2003 to 2005 and constant after 2005. For selenium and zinc no previous Danish data are available therefore it has been assumed that the reduction since year 2000 for these two pollutants have been similar to that of lead. The choice of the lead emission factor as surrogate data is based on the high number of measurements for lead and that only a few of the measurements are below the detection limit. The HCB emission factor for 1990 has been established according to the EMEP/EEA Guidebook (EEA, 2009); the time-series trend has been assumed to follow the trend for PCDD/-F.

Emission factor time-series for SO_2, NO_x, NMVOC, CH_4, CO, N_2O, TSP, metals, HCB, PCDD/-F and the four PAH reported to the Convention on Long-Range Transboundary Air Pollution has been developed.

The emission factor for NH_3 is used for all years.

Several of the emission measurements are below the detection limit and this complicates making firm conclusions regarding the trend of the emission factor time-series. For the three priority metals (cadmium, lead & mercury) there have been calculated intervals for the emission factors based on the detection limit and zero for both 2000 and 2006. These intervals including the reduction intervals are shown in Table 5.18. The calculation proves that the lower emission factors in 2006 are not explained only by a lower detection limit.

Table 5.18 Emission factors and reduction intervals for cadmium, lead and mercury.

	2000		2006		Reduction	Reduction interval
	Zero	Detection limit	Zero	Detection limit		
Cadmium	2.9 -	4.8	0.21 -	0.44	91 %	85 % - 96 %
Mercury	2.9 -	7.4	1.71 -	1.79	76 %	38 % - 77 %
Lead	51 -	123	0.79 -	5.52	96 %	89 % - 99 %

5.14.2 Straw

Emission factor time-series for straw fired plants has not been elaborated. All emission factors are used for the entire time-series.

5.14.3 Wood

Emission factor time-series for wood fired plants has not been elaborated. All emission factors are used for the entire time-series.

5.14.4 Natural gas powered engines

For natural gas powered engines new emission limit values entered into force in October 2006. There are therefore three relevant data sets: The emission factors for year 2000, the emission factors calculated for 2003 to 2006 and the emission factors calculated for 2007 onwards. The emission factors based on measurements from the period 2003 to 2006 are shown in Table 5.19.

Emission factor time-series for the period 2000-2007 has been estimated for NO_x, NMVOC, CH_4, CO and the four PAH reported to UNECE.

The emission factor for N_2O will be used for the entire time-series (1990 onwards) even though an emission factor were estimated for the year 2000 in 2003, see Chapter 5.6 for further discussions on this issue.

The calculated emission factors for heavy metals and PCDD/-F will be used for the entire time-series (1990 onwards).

The emission factors based on measurements from 2003 to 2006 have been used for 2005. A linear trend has been assumed from 2000 to 2005 and from 2005 to 2007. Hereafter the emission factors

have been assumed constant. The emission factors for year 2000 refer to the full load emission factors calculated in a previous emission factor survey (Nielsen & Illerup, 2003) and the correction factors for start-up and shut-down developed in a previous project (Nielsen et al., 2008). For the four PAH the trend has been assumed linear between 2000 and 2007.

The emission factor time-series is shown in Figure 5.4. The emission factors for CH_4 and NMVOC increase slightly from 2005 to 2007, while the emission factors for NO_x and CO are decreasing through the whole time-series.

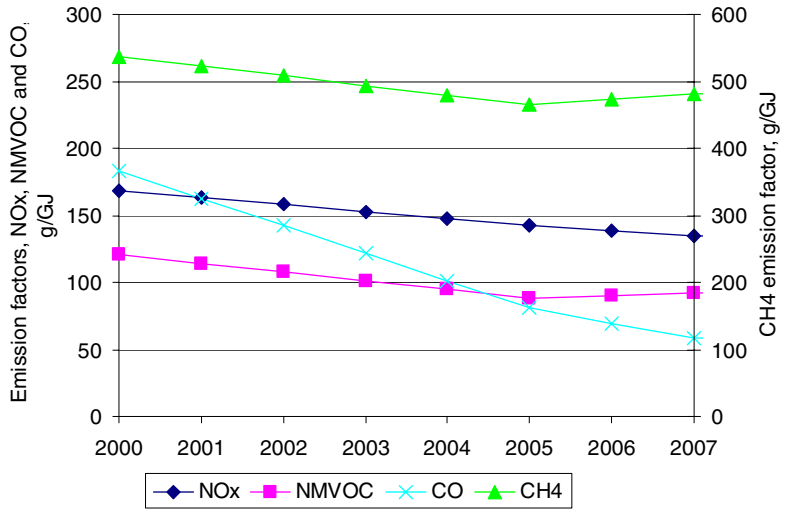


Figure 5.4 Time-series for emission factors, natural gas powered engines.

Emission factors for natural gas powered engines, 2003-2006

Full load emission factors for natural gas powered engines based on measurements from 2003-2006 are shown in Table 5.19. There were 368 data sets available for the period 2003-2006. Detailed data including minimum, maximum and standard deviation are shown in Appendix 6.

For NO_x, UHC and NMVOC the increased emissions during start-up and shut-down have been included in calculating the emission factors. These emission factors are shown in Table 5.19.

Table 5.19 Emission factors for natural gas powered engines, 2003-2006.

	Unit	Emission factor full load	Emission factor incl. start/stop emissions
NO_x	g per GJ	143	143
UHC (C)	g per GJ	406	420
NMVOC	g per GJ	86	88
CH_4	g per GJ	450	465
CO	g per GJ	77	81
Formaldehyde	g per GJ	12	-
Acetaldehyde	g per GJ	0.68	-
Acrolein	g per GJ	0.033	-
Propanal	g per GJ	0.044	-
Acetone	g per GJ	0.072	-
Butanal	g per GJ	0.006	-
Pentanal	g per GJ	-	-
Hexanal	g per GJ	0.010	-
Benzaldehyde	g per GJ	0.0020	-
Odour	OU per m^3	7809	-
Electrical efficiency	%	39.4	-

5.14.5 Biogas powered engines

For biogas powered engines new emission limit values do not enter into force before 2013. There has been assumed en linear trend from 2000 to 2006. For NO_x, NMVOC, CH_4, CO and the four reported PAHs time-series have been calculated for the years 2000-2006.

The emission factors for N_2O, metals, PCDD/-F and HCB will be used for the entire time-series.

5.14.6 Natural gas powered gas turbines

For natural gas powered gas turbines new emission limit values entered into force in October 2006. There are therefore three relevant data sets: The emission factors for year 2000, the emission factors calculated for 2003 to 2006 and the emission factors calculated for 2007 onwards. The emission factors based on measurements from the period 2003 to 2006 are shown in Table 5.20.

Emission factor time-series for the period 2000-2007 has been estimated for NO_x, NMVOC, CH_4, CO and N_2O.

The emission factors based on measurements from 2003 to 2006 have been used for 2005. For CO and NO_x a linear trend has been assumed from 2000 to 2005 and from 2005 to 2007. Hereafter the emission factors have been assumed constant. The emission factors for year 2000 refer to the full load emission factors calculated in a previous emission factor survey (Nielsen & Illerup, 2003).

The emission factors for NMVOC and CH_4 are based on measurements from the period 2003-2006. Since no newer measurements

are available it has been assumed that the emission factor trend from 2000 to 2005 was linear. The emission factors have been kept constant from 2005 onwards.

For N_2O a linear trend has been assumed from 2000 to 2007, hereafter the emission factor is kept constant.

The emission factor time-series is shown in Figure 5.5. The emission factors for CH_4 and NMVOC increase slightly through the time-series, while the emission factors for NO_x and CO have decreased - especially from 2005 to 2007.

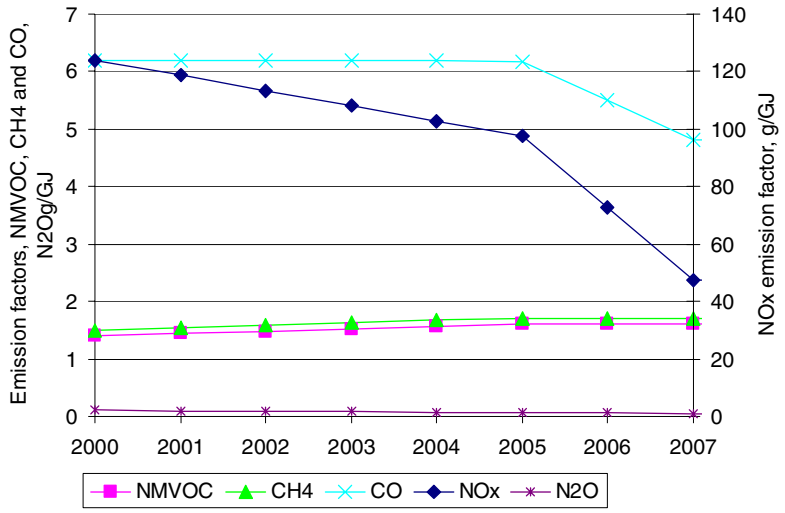


Figure 5.5 Time-series for emission factors, natural gas powered gas turbines.

Emission factors for natural gas powered gas turbines 2003-2006

Full load emission factors for natural gas powered gas turbine based on measurements from 2003-2006 are shown in Table 5.20. Twenty-two data sets were available. Detailed data including minimum, maximum and standard deviation are included in Appendix 8.

Table 5.20 Emission factors for natural gas powered gas turbines, 2003-2006.

	Unit	Emission factor
NO_x	g per GJ	98
UHC (C)	g per GJ	2.5
NMVOC	g per GJ	1.6
CH_4	g per GJ	1.7
CO	g per GJ	6.2
Electrical efficiency	%	28.8

5.14.7 Oil

For gas oil powered engines all the calculated emission factors have been applied for the entire time-series. SO_2 was not measured in this project; therefore existing emission factor time-series has not been changed.

For gas oil powered gas turbines only emission factors for NO_x and CO have been calculated. The previous NO_x emission factor referred to plant specific data for larger plants obtained in 2001. There have been made a time-series for the NO_x emission factor assuming a linear reduction between 2001 and 2006. The CO emission factor calculated in this project has been applied for all years.

For fuel oil powered steam turbines the previously used emission factor is based on plant specific data from larger plants, and this emission factor has been updated annually. The emission factor calculated in this project will be used back to the year 2000, for the preceding years the existing time-series of emission factors will continue to be used. The other calculated emission factors will be used for all years; the emission factor for CO will only be applied back to the year 2000[34].

5.14.8 Biomass producer gas

Previously emission factors for biomass producer gas have not been estimated; therefore the emission factors calculated in this project will be used for the entire time-series.

[34] For years prior to 2000 an emission factor of 5 g per GJ is used. This emission factor refer to EMEP/EEA Guidebook (EEA, 2009)

6 Evaluation of the potential impact of PBDD/-F, PCB and HCB

6.1 PBDD/-F

PBDD/-F was included in the measurement programme as screening components. The data set includes waste incineration, biogas fuelled engines and engines using biomass producer gas based on wood. The reason for including PBDD/-F in the measurement programme was the extensive use of brominated flame retardants PentaBDE and OctaBDE, which now has been prohibited. The use of these flame retardants contributes to the unintentional formation of PBDD/-F.

The detection limit for PBDD/-F proved to be higher than the detection limit for PCDD/-F. Sine all measurements of PBDD/-F were below the detection limit it is connected with large uncertainties to conclude anything regarding the emission level for PBDD/-F.

Based on the measurement data it can not be ruled out that the emission of PBDD/-F is at the same level or higher than the emission of PCDD/-F.

From a toxicology point of view the emission of brominated flame retardants is of concern since the measurements included in this project only cover a small number of the possible congeners. Only the sum of the assumed most toxic single congeners of pure PBDD/-F are included. This means that the mixed congeners are not included. The mixed congeners include almost 1 000 possible 2,3,7,8 congeners versus the 17 most toxic PBDD/-F congeners (Söderström & Marklund, 2002).

6.2 PCB

PCBs were included in the measurement programme as screening components. The data set includes waste incineration, biogas fuelled engines, gas oil powered engines and engines using biomass producer gas based on woody biomass.

PCB is together with other POP compounds recommended to be reported in the national emission inventory to the UNECE convention on Long-Range Transboundary Air Pollution. PCBs are also a source of emissions of PCDD/-F from waste incineration plants.

For PCB it has been important to acquire the documentation to facilitate the calculation a more certain Danish emission factor, since previous studies indicate significantly varying levels and a large

uncertainty. The previously assumed level in Denmark was lower than the information acquired from other countries (Thomsen et al., 2009).

All measurements from the engine plants were below the detection limit, therefore the calculated emission factors are based on the detection limits. For waste incineration plants several congeners are above the detection limit. The emission contribution from waste incineration is as expected the largest. The estimated emission factor is significantly lower than the emission factor from previous studies (Thomsen et al., 2009).

6.3 HCB

HCB was included in the measurement programme as screening components. The data set includes waste incineration, biogas fuelled engines, gas oil powered engines, engines using biomass producer gas based on woody biomass and straw fired plants.

HCB is part of the Danish national emission inventory and is reported to the UNECE convention on Long-Range Transboundary Air Pollution.

HCB is not used in Denmark and therefore it is only emitted through the unintentional formation during combustion processes with chlorine present.

As expected the largest source of HCB emission is waste incineration. Even though the calculated emission is significantly reduced compared to the previous emission inventory, decentralised CHP production, in particular waste incineration, is one of the dominant sources to HCB emission in Denmark.

7 Emission inventory for decentralised CHP production

7.1 Data sources for the emission inventory

The emission inventory for decentralised CHP production for 2006 is based on:

- Survey of electricity and heat producing plants for the year 2006 (DEA, 2007).
- Emission factors for 2006, which is calculated in this project, see Table 5.21 in Chapter 5.13. For natural gas emission factors for 2007 is used.
- NERI's standard emission factors for the emission factors not included in this project.
- Emission factors from an earlier project (Nielsen & Illerup, 2003) if not included by the two sources above.

Plants with an electrical capacity less than 25 MW_e are included, unless they are placed at centralised plants.

Consumption of secondary fuels on the plants is included. Therefore there are small deviations from the fuel consumption data presented in the chapters on plant characterisation (Chapter 3). The consumption of straw and wood at Grenå Kraftvarmeværk and the consumption of straw at Thisted Kraftvarmeværk are included in the inventory. The consumption of gas oil in dual fuel engines is included under gas oil engines. The consumption of gas oil in steam turbine plants and multi fuel plants is included under gas oil powered gas turbines.

7.2 Emission factors and fuel consumption 2006

The fuel consumption data and the emission factors used in the calculation of the emissions from decentralised CHP production are shown in Table 7.1. The emission factors that are not calculated in this project and which are instead referring to the national emission database or the earlier project are marked with grey.

Fuel consumption in plants located at centralised power plants is not included even if the single production unit is smaller than 25 MW_e. The consumption of gas oil in multi fuel plants and steam turbine plants is included under gas oil powered gas turbines.

Table 7.1 Fuel consumption and emission factors used for decentralised CHP plants.

	Unit	Natural gas, engines	Biogas, engines	Natural gas, turbines	Gas oil, engines	Gas oil, gas turbines	Fuel oil, stem turbines	Biomass producer gas, engines	Waste	Straw	Wood
Fuel consumption	g per GJ	28033	3125	6907	30	75	2284	66	33728	3139	3562
SO_2	g per GJ	0.3	19.2	0.3	23	23	308	1.88	8.3	49	1.9
NO_x	g per GJ	135	202	48	942	83	136	173	102	125	81
UHC	g per GJ	435	333	2.5	46	3	1.6	12	0.68	0.94	6.1
NMVOC	g per GJ	92	10	1.6	37	2	0.8	2.3	0.56	0.78	5.1
CH_4	g per GJ	481	434	1.7	24	1.5	1.3	13	0.34	0.47	3.1
CO	g per GJ	58	310	4.8	130	2.6	2.8	586	3.9	67	90
N_2O	g per GJ	0.58	1.6	1.0	2.1	NE	5.0	2.7	1.2	1.1	0.83
NH_3	g per GJ	NE	NE	NE	NE	NE	NE	NE	0.29	NE	NE
TSP	mg per GJ	0.76	2.63	0.10	5	5	9.5	7.9	0.29	2.3	10
As	mg per GJ	0.045	0.042	0.045	0.055	0.055	14.07	0.12	0.59	2.0	2.34
Cd	mg per GJ	0.003	0.002	0.003	0.011	0.011	13.5	0.009	0.44	0.32	0.27
Co	mg per GJ	0.20	0.21	0.20	0.28	0.28	NE	0.223	0.56	NE	NE
Cr	mg per GJ	0.048	0.18	0.048	0.20	0.20	33.33	0.029	1.6	1.52	2.34
Cu	mg per GJ	0.015	0.31	0.015	0.30	0.30	12.96	0.045	1.3	1.66	2.6
Hg	mg per GJ	0.098	0.12	0.098	0.11	0.11	4.3	0.54	1.8	0.31	0.40
Mn	mg per GJ	0.046	0.19	0.046	0.009	0.009	NE	0.008	2.1	NE	NE
Ni	mg per GJ	0.045	0.23	0.045	0.013	0.013	642	0.014	2.1	1.62	2.34
Pb	mg per GJ	0.043	0.005	0.043	0.15	0.15	23.46	0.022	5.5	6.12	3.62
Sb	mg per GJ	0.049	0.12	0.049	0.055	0.055	NE	0.045	1.1	NE	NE
Se	mg per GJ	0.01	0.21	0.01	0.22	0.22	12.30	0.18	1.1	NE	NE
Sn	mg per GJ	NE	NE	NE	NE	NE	NE	NE	1.0	NE	NE
Tl	mg per GJ	0.20	0.21	0.20	0.22	0.22	NE	0.18	0.45	NE	NE
V	mg per GJ	0.048	0.042	0.048	0.007	0.007	NE	0.045	0.33	NE	NE
Zn	ng per GJ	2.9	4.0	2.9	58	58	2.72	0.06	2.3	8.39	2.3
PCDD/-F	ng per GJ	0.57	0.96	0.025	0.99	0.882	0.882	1.7	5.0	22	14
PBDD/-F	µg per GJ	NE	5.0	NE	NE	NE	NE	7.2	6.3	NE	NE
PAH (BaP)	µg per GJ	13	4.2	5	33	NE	NE	5	2	125	13
ΣPAH	µg per GJ	1025	606	83	8988	NE	NE	181	37	5946	664
Naphthalene	µg per GJ	2452	4577	300	17642	NE	NE	8492	129	12088	2314
HCB	ng per GJ	NE	0.19	NE	0.22	NE	NE	0.80	4	0.11	4
PCB	g per GJ	NE	0.19	NE	0.13	NE	NE	0.24	0.32	NE	NE
Formaldehyde	g per GJ	14.1	8.7	0.01	1.3	NE	0.002	1.5	NE	NE	NE
Acetaldehyde	g per GJ	1.01	0.12	NE	0.40	NE	0.001	0.56	NE	NE	NE
Acrolein	g per GJ	0.016	0.001	NE	0.002	NE	0.001	0.001	NE	NE	NE
Propanal	g per GJ	0.078	0.023	NE	0.045	NE	0.001	0.048	NE	NE	NE
Acetone	g per GJ	0.45	0.023	0.01	0.082	NE	0.004	0.56	NE	NE	NE
Butanal	g per GJ	0.071	0.001	0.01	0.055	NE	0.001	0.001	NE	NE	NE
Pentanal	g per GJ	0.012	0.001	NE	0.007	NE	0.001	0.001	NE	NE	NE
Hexanal	g per GJ	0.006	0.001	NE	0.002	NE	0.001	0.001	NE	NE	NE
Benzaldehyde	g per GJ	0.002	0.013	NE	0.029	NE	0.001	0.14	NE	NE	NE
HCl	g per GJ	NE	NE	NE	NE	NE	NE	NE	1.14	56	0.9
HF	g per GJ	NE	NE	NE	NE	NE	NE	NE	0.14	0.2	0.09

Grey cells indicate an emission factor not referenced to this project. NE: Not Estimated.

7.3 Emission inventory 2006

The total emissions from decentralised CHP production in 2006 are shown in Table 7.2. A similar table that shows the percentage distribution is included in Appendix 13.

Waste incineration had the highest fuel consumption at decentralised CHP plants in 2006 (42 %). Natural gas engines accounted for 35 % of the total fuel consumption at decentralised CHP plants. Natural gas powered gas turbines, including the full consumption in combined cycle plants, accounted for 9 %, while the fuel consumption in straw and wood fired plants and fuel oil powered steam turbines each accounted for less than 5 %. The consumption of biomass producer gas and gas oil were each less than 1 % in 2006.

Natural gas engines are the major emission source of CH_4, NMVOC and aldehydes. The emission of PAH expressed as ΣPAH from natural gas engines accounts for a little more than 50 %. Natural gas engines were in 2006 the largest emission source for CO (49 %), NO_x (41 %) and Zn (34 %). The high share for zinc is probably due to the consumption of lubricants in the engines.

Waste incineration plants are the largest emission source for most heavy metals, N_2O, HF, PCDD/-F, HCB and PCB. Waste incineration also contributes significantly to the emissions of NO_x (37 %) and SO_2 (23 %). NH_3 has only been measured from waste incineration plants.

The calculated emission of PBDD/-F from waste incineration is higher than for the other plant types. However, since all the measurements for all congeners for all plant types were below the detection limit, no conclusions can be made as to which plant type contributes the most.

Straw fired plants are the largest source of HCl and also a significant source of PAH expressed as ΣPAH (31 %). Wood fired plants are the largest source of emission of particulate matter. Both wood and straw fired plants contribute significantly to the emission of PCDD/-F.

Fuel oil powered steam turbines are the largest emission source for SO_2 and for some metals. The heavy metal emission factors for fuel oil have not been estimated in this project but refer to the national emission database. These emission factors have not been updated for several years, and in the light of the large reductions observed for waste incineration plants, NERI will evaluate and if deemed necessary update heavy metal emission factors for other fuels that have not previously been significant sources to the total emission of heavy metals. The SO_2 emission factor for fuel oil should also be updated.

Biogas engines are a significant source of CO emission (39 %) but for the remaining pollutants the contribution to the total emission is very limited.

The contribution to the total emissions from decentralised CHP production is low for natural gas turbines, gas oil fired plants and biomass producer gas.

In Chapter 8 the emissions from decentralised CHP production are compared with the total Danish emissions.

Table 7.2 Emission inventory for decentralised CHP production 2006.

	Unit	Natural gas, engines	Biogas, engines	Natural gas, turbines	Gas oil, engines	Gas oil, gas turbines	Fuel oil, stem turbines	Biomass producer gas, engines	Waste	Straw	Wood	Total
Fuel consumption	TJ	28 033	3125	6907	30	75	2284	66	33 728	3139	3562	80 950
SO_2	Mg	8	60	2	1	2	704	0	279	153	7	1215
NO_x	Mg	3781	632	329	29	6	310	11	3453	393	290	9234
UHC	Mg	12 186	1041	17	1	0	4	1	23	3	22	13 298
NMVOC	Mg	2568	30	11	1	0	2	0	19	2	18	2652
CH_4	Mg	13 495	1357	12	1	0	3	1	11	1	11	14 892
CO	Mg	1633	970	33	4	0	6	39	132	212	322	3352
N_2O	Mg	16	5	7	0	NE	11	0	42	4	3	88
NH_3	Mg	NE	NE	NE	NE	NE	NE	NE	10	NE	NE	10
TSP	Mg	21	8	1	0	0	22	1	10	7	36	106
As	kg	1.26	0.13	0.31	0.00	0.00	32	0.01	20.02	6.28	8.33	68
Cd	kg	0.08	0.01	0.02	0.00	0.00	31	0.00	14.81	1.01	0.97	48
Co	kg	5.72	0.65	1.41	0.01	0.02	NE	0.01	19.01	NE	NE	27
Cr	kg	1.34	0.57	0.33	0.01	0.01	76	0.00	52.60	4.77	8.33	144
Cu	kg	0.42	0.98	0.10	0.01	0.02	30	0.00	43.81	5.21	9.26	89
Hg	kg	2.76	0.39	0.68	0.00	0.01	10	0.04	60.30	0.96	1.44	76
Mn	kg	1.28	0.59	0.32	0.00	0.00	NE	0.00	72.24	NE	NE	74
Ni	kg	1.27	0.73	0.31	0.00	0.00	1467	0.00	69.31	5.09	8.33	1552
Pb	kg	1.21	0.01	0.30	0.00	0.01	54	0.00	186.19	19.21	12.89	273
Sb	kg	1.38	0.39	0.34	0.00	0.00	NE	0.00	38.40	NE	NE	41
Se	kg	0.28	0.65	0.07	0.01	0.02	28	0.01	37.30	NE	NE	66
Sn	kg	NE	NE	NE	NE	NE	NE	NE	35.33	NE	NE	35
Tl	kg	5.51	0.65	1.36	0.01	0.02	NE	0.01	15.07	NE	NE	23
V	kg	1.35	0.13	0.33	0.00	0.00	NE	0.00	11.03	NE	NE	13
Zn	kg	81.70	12.35	20.13	1.76	4.37	6.2	0.00	78.72	26.34	8.33	240
PCDD/-F	mg	15.88	2.99	0.17	0.03	0.07	2.0	0.12	167.36	69.06	51.16	309
PBDD/-F	mg	NE	15.6	NE	NE	NE	NE	0.5	211	NE	NE	227
PAH (BaP)	kg	0.361	0.013	0.035	0.001	NE	NE	0.000	0.074	0.391	0.047	0.92
ΣPAH	kg	29	2	0.6	0.3	NE	NE	0.01	1.3	19	2	54
Naphthalene	kg	69	14	2	0.5	NE	NE	0.6	4	38	8	137
HCB	g	NE	0.60	NE	0.01	NE	NE	0.05	145	0.4	14	160
PCB	mg	NE	0.60	NE	0.00	NE	NE	0.02	11	NE	NE	11
Formaldehyde	Mg	396	27	0.069	0.040	NE	0.005	0.101	NE	NE	NE	423
Acetaldehyde	Mg	28	0.36	NE	0.012	NE	0.003	0.037	NE	NE	NE	29
Acrolein	Mg	0.44	0.003	NE	0.000	NE	0.003	0.000	NE	NE	NE	0.4
Propanal	Mg	2.18	0.071	NE	0.001	NE	0.003	0.003	NE	NE	NE	2
Acetone	Mg	12.8	0.073	0.069	0.002	NE	0.009	0.037	NE	NE	NE	13
Butanal	Mg	2.0	0.003	0.069	0.002	NE	0.003	0.000	NE	NE	NE	2
Pentanal	Mg	0.33	0.004	NE	0.000	NE	0.003	0.000	NE	NE	NE	0.3
Hexanal	Mg	0.18	0.003	NE	0.000	NE	0.003	0.000	NE	NE	NE	0.2
Benzaldehyde	Mg	0.053	0.040	NE	0.001	NE	0.003	0.010	NE	NE	NE	0.1
HCl	Mg	NE	NE	NE	NE	NE	NE	NE	38	175	3	216
HF	Mg	NE	NE	NE	NE	NE	NE	NE	4.6	0.6	0.3	6

NE: Not Estimated.

8 Emission share from decentralised CHP production compared to national total

Table 8.1 shows the calculated emissions from decentralised CHP production in 2006 compared with the national emissions reported under the Climate Convention (Nielsen et al., 2009a) and the Convention on Long-Range Transboundary Air Pollution (Nielsen et al., 2009b). The emissions from decentralised CHP production are compared to:

- Sector *1A1a Public electricity and heat production*[35]
- Sector *1A Fuel combustion*[36]
- The total national emission[37]

In addition to emission data Table 8.1 also shows the percentage emission share from decentralised CHP production compared to the national emissions, the total emissions from fuel combustion and the emissions from public electricity and heat production.

Energinet.dk uses the emission factors to calculate the total emission from production of electricity and to calculate an environmental impact statement for electricity. In the national emission inventory there is not a sector encompassing all electricity production. For instance industrial combustion is in the national inventory included under industrial combustion (sector *1A2 Manufacturing Industries and Construction*). A comparison with the sector *1A1a Public electricity and heat production* gives an indicative impression of the significance of the emissions from decentralised CHP production compared to the total emissions from electricity production.

The SO_2 and NO_x emissions from decentralised CHP production in 2006 added up to 5 % of the national total. The CH_4 emission was 6 % of the national total while the emission of several heavy metals from decentralised CHP production added up to more than 10 % of the national total. The emission contribution for HCB was at 30 % but the inventory for HCB is not complete regarding sources. For dioxin the emission from decentralised CHP production is only 1 %; this is a significant reduction compared to 1995 where the emission share was 35 %.

If the emission from decentralised CHP production is compared to sector *1A1a* it is seen that the emission of CH_4 is higher (23 %). This is due to the fact mentioned above that some decentralised CHP plants are included in other sectors. CH_4 emissions mainly originate from gas engines and some of these gas engines are installed at industrial plants. The emission of NMVOC almost exclusively stem from gas engines, which are all decentralised plants; the emission share compared to *1A1a* is 90 %.

[35] The emission source category *1A1a Public electricity and heat production* does not include auto producers.
[36] The emission source category *1A Fuel combustion* includes combustion in transport and other mobile sources
[37] Emissions from Denmark, excluding Greenland and the Faroe Islands.

Decentralised CHP production is also a significant source of NO_x, CO metals and POPs.

Table 8.1 Decentralised CHP plants share of total national emissions, 2006.

	Unit	Decentral-ised CHP production	1A1a Pub-lic electric-ity and heat production[1)]	1A Fuel combustion[1)]	National total[1)]	1A1a Public electricity and heat production	1A Fuel combustion	National total
Fuel con-sumption	TJ	80 950	386 495	842 188	-	21 %	10 %	-
SO_2	Mg	1215	9761	24 225	25 423	12 %	5 %	5 %
NOx	Mg	9234	35 578	172 828	173 124	26 %	5 %	5 %
NMVOC	Mg	2652	2935	60 137	107 085	90 %	4 %	2 %
CH_4	Mg	14 892	12 068	24 683	268 595	123 %	60 %	6 %
CO	Mg	3352	8368	437 320	437 785	40 %	1 %	1 %
N_2O	Mg	88	374	1442	20 839	24 %	6 %	0.4 %
NH_3	Mg	10	-	2303	75 707	-	0.4 %	0.01 %
TSP	Mg	106	954	32 179	48 324	11 %	0.3 %	0.2 %
As	kg	68	174	495	495	39 %	14 %	14 %
Cd	kg	48	96	587	592	50 %	8 %	8 %
Cr	kg	144	336	1165	1165	43 %	12 %	12 %
Cu	kg	89	302	9134	9180	30 %	1 %	1 %
Hg	kg	76	430	1036	1082	18 %	7 %	7 %
Ni	kg	1552	1985	10 370	10 370	78 %	15 %	15 %
Pb	kg	273	721	3357	3425	38 %	8 %	8 %
Se	kg	66	1108	1945	1946	6 %	3 %	3 %
Zn	kg	240	2224	13 412	14 054	11 %	2 %	2 %
PCDD/-F	mg	309	1135	18 917	25 073	27 %	2 %	1 %
HCB	g	160	268	526	532	60 %	30 %	30 %

[1)] Total emissions from NERI's reporting of national emissions for 2006 (Nielsen et al., 2009a, Nielsen et al., 2009b) corrected according to the new emission factors calculated in this project.

9 Uncertainties

DGC and FORCE Technology have calculated uncertainties for the majority of the emission factors. The calculation and underlying methodology is described in project report 3 (Boje et al., 2010b) and project report 4 (Jørgensen et al., 2010b).

10 Conclusion

Based on project measurements and collected measurement data updated emission factors for decentralised CHP production has been calculated for the year 2006/2007. An excerpt of the emission factors are shown in Table 10.1. The emission factors for natural gas powered gas turbines and engines are calculated for 2007 due to the new emission limit values for these plant types that entered into force in 2007.

Table 10.1 Excerpt of the calculated emission factors for decentralised CHP production.

	Unit	Natural gas, engines	Biogas, engines	Natural gas, gas turbines	Gas oil, engines	Gas oil, gas turbines	Fuel oil, steam turbine	Biomass producer gas, engines	Waste incinera-tion plants	Straw fired plants	Wood fired plants
SO_2	g per GJ	-	-	-	-	-	-	-	< 8.3	49	< 1.9
NO_x	g per GJ	135[8)]	202	48	942	83	136	173	102	125	81
UHC (C)	g per GJ	435[8)]	333	2.5[9)]	(46) [10)]	-	(1.6) [10)]	12	< 0.68	< 0.94[5)]	< 6.1[6)]
NMVOC	g per GJ	92[4) 8)]	10[4)]	1.6[4)]	(37)[10)]	-	(0.8) [10)]	2.3[4)]	< 0.56[4)]	< 0.78[4)]	< 5.1[4)]
CH_4	g per GJ	481[4) 8)]	434[4)]	1.7[4)]	24	-	< 1.3	13[4)]	< 0.34[4)]	< 0.47[4)]	< 3.1[4)]
CO	g per GJ	58[8)]	310	4.8	130	2.6	2.8	586	< 3.9	67	90
N_2O	g per GJ	0.58	1.6	1.0	2.1	-	5.0	2.7	1.2	1.1	0.83
NH_3	g per GJ	-	-	-	-	-	-	-	< 0.29	-	-
TSP	g per GJ	-	-	-	-	-	9.5	-	< 0.29	< 2.3	10
As	mg per GJ	< 0.045	< 0.042	-	< 0.055	-	-	0.116	< 0.59	-	-
Cd	mg per GJ	< 0.003	0.002	-	< 0.011	-	-	< 0.009	< 0.44	< 0.32[3)]	0.27
Co	mg per GJ	< 0.20	< 0.21	-	< 0.28	-	-	< 0.22	< 0.56	-	-
Cr	mg per GJ	0.048	0.18	-	0.20	-	-	0.029	< 1.6	-	-
Cu	mg per GJ	0.015	0.31	-	0.30	-	-	< 0.045	< 1.3	-	-
Hg	mg per GJ	< 0.098[3)]	< 0.12	-	< 0.11	-	-	0.54	< 1.8	< 0.31[3)]	< 0.40[3)]
Mn	mg per GJ	< 0.046	0.19	-	0.009	-	-	0.008	< 2.1	-	-
Ni	mg per GJ	0.045	0.23	-	0.013	-	-	0.014	< 2.1	-	-
Pb	mg per GJ	0.043	0.005	-	0.15	-	-	0.022	< 5.5	-	-
Sb	mg per GJ	< 0.049[3)]	0.12	-	< 0.055	-	-	< 0.045	< 1.1	-	-
Se	mg per GJ	(0.01)[7)]	< 0.21	-	< 0.22	-	-	< 0.18	< 1.1	-	-
Tl	mg per GJ	< 0.20[3)]	< 0.21	-	< 0.22	-	-	< 0.18	< 0.45[3)]	-	-
V	mg per GJ	< 0.048	< 0.042	-	0.007	-	-	< 0.045	< 0.33	-	-
Zn	mg per GJ	2.9	4.0	-	58	-	-	0.058	2.3	0.41	2.3
PCDD/-F	ng per GJ	< 0.57	< 0.96[1)]	-	< 0.99	-	-	< 1.7[1)]	< 5.0	< 19	< 14
PBDD/-F	ng per GJ	-	< 5.0[1)]	-	-	-	-	< 7.2[1)]	< 6.3[1)]	-	-
PAH (BaP)	µg per GJ	< 13	< 4.2	-	< 33	-	-	< 4.9	< 2	< 125	< 13
ΣPAH	µg per GJ	< 1025	< 606	-	< 8988	-	-	< 181	< 37	< 5946	< 664
Naphthalene	µg per GJ	2452	4577	-	17642	-	-	8492	< 129[3)]	12088	2314
HCB	µg per GJ	-	0.19	-	< 0.22	-	-	0.80	< 4.3	< 0.11	-
PCB	ng per GJ	-	< 0.19[1)]	-	< 0.13[1)]	-	-	< 0.24[1)]	< 0.32	-	-
Formaldehyde	g per GJ	14.1	8.7	-	1.3	-	< 0.002	1.5	-	-	-
HCl	g per GJ	-	-	-	-	-	-	-	< 1.14	56	-
HF	g per GJ	-	-	-	-	-	-	-	< 0.14	-	-

[1)] The measurements for all congeners were below the detection limit.
[2)] Based on a single measurement below the detection limit.
[3)] All measurements were below the detection limit.
[4)] Based on a distribution key for UHC.
[5)] Only one of seven measurements was above the detection limit.
[6)] Two out of three measurements were below the detection limit.
[7)] Two emission measurements were performed, both below the detection limit. These results have been ignored and instead the lower emission factor 0.01 mg per GJ based on EEA (2009) have been applied.
[8)] The increased emission level during start up and stop of the gas engines have been included in this emission factor.
[9)] Based on emission measurements performed in 2003-2006.
[10)] The emission factor based on emission measurements performed within this project has been ignored. Instead the NMVOC emission factor refers to EEA (2009). The UHC emission factor has been estimated based on the emission factors for NMVOC and CH_4.

The emission factors for waste incineration plants are much lower than the emission factors that were estimated for year 2000. The considerable reduction in the emission factors is a result of lower emission limit values in Danish legislation (DEPA, 2003). This has lead to installation of

new and improved flue gas cleaning systems in most waste incineration plants. The TSP emission factor is 86 % lower than the emission factor in 2000, whereas the reduction for heavy metal emission factors is 38 % to 96 %. For dioxin (PCDD/-F) the emission factor has decreased 97 % since year 2000 due to the fact that dioxin flue gas cleaning have been installed in all MSW incineration plants as a result of the new emission limit values (DEPA, 2003). Emission factors for NO_x, SO_2, HCl and HF have also decreased considerably since year 2000.

Combined heat and power (CHP) plants combusting straw and wood have not undergone major changes in technology or flue gas cleaning systems since year 2000 and the emission limit values are also unchanged. The relatively low number of plants and emission measurements results in uncertainty concerning development of the emission levels of these plant categories. Emission measurements from the years 2000-2008 have been included in the estimates. A large variability in the emission levels for single plants has been observed.

The emission factors for natural gas fuelled reciprocating engines have been reduced since 2000 as a result of technical improvements that have been carried out as a result of lower emission limit values in Danish legislation (DEPA, 2005). Most engines had to be below the lower emission limit values in October 2006 and thus the emission factors have been estimated for 2007 onwards. The NO_x emission factor has decreased 20 % and the CO emission factor has decreased 68 % since 2000 due to the installation of oxidation catalysts. The UHC emission has also decreased since 2000. The CH_4 emission factor has decreased 10 % and the NMVOC 24 %.

The fuel consumption for biogas fuelled engines has increased 32 % since 2000. The increase is mainly on larger engines. This is part of the reason for the changes of emission factors for biogas fuelled engines. Lower emission limit values for biogas fuelled engines > 1 MW is included in Danish legislation (DEPA, 2005), but the engines do not have to meet these emission limits until 2013. The emission factor for NO_x has decreased 63 % since 2000 whereas the emission factor for UHC has increased 31 %. The CO emission factor is 14 % higher than in 2000.

The NO_x emission factor for natural gas fuelled gas turbines has decreased 62 % since 2000. This is a result of installation of low-NO_x burners in almost all gas turbines. This has been necessary to meet new emission limits in Danish legislation (DEPA, 2005).

Emission factors have also been estimated for CHP plants combusting oil and biomass producer gas, respectively. For gas oil fuelled engines the NO_x emission factor is remarkably high compared to other CHP plants. The CO emission factor for engines fuelled by biomass producer gas is considerably higher than for other engines whereas the UHC emission is much lower. This is in agreement with the composition of the biomass producer gas, which has a high CO content and a low content of hydrocarbons.

The emission measurements performed in this project included screening of a number of emissions that have not previously been measured from Danish CHP plants. The measurements of PBDD/-F were below

the detection limits for all congeners at all plant types. The detection limit for PBDD/-F was higher than the detection limit for PCDD/-F and thus the data for PBDD/-F added limited new information. Based on the PBDD/-F measurements performed in this project it could not be ruled out that the PBDD/-F emission is higher than the PCDD/-F emission.

A few PCDD/-F congeners were above the detection limit for gas oil fuelled engines and natural gas fuelled engines, whereas all congeners were below the detection limit for biomass producer gas fuelled engines. Further PCDD/-F emissions above the detection limit were measured for MSW incineration plants and for straw and wood fuelled CHP plants.

PCB emission measurements performed at engines fuelled by gas oil, biogas and biomass producer gas were below the detection limit for all congeners. For waste incineration plants several PCB emission measurements were above the detection limit. The PCB emission factors are below the emission factors stated in a former study (Thomsen et al., 2009).

As expected waste incineration plants are the main emission source for HCB. In spite of the fact that the estimated HCB emission factor for waste incineration is much lower than the current factor, waste incineration is still among the main emission sources for HCB in Denmark.

Uncertainty estimates for the emission factors have been estimated and reported in project report 3 (Boje et al., 2010b) and project report 4 (Jørgensen et al., 2010b).

Total emissions from decentralized CHP plants <25MW_e have been estimated for 2006. This estimate shows that natural gas fuelled engines was the main emission source for CH_4, NMVOC and aldehydes. Further, natural gas fuelled engines was the largest emission source for CO (49 %) and NO_x (41 %) and, unexpectedly, also for Zn (34%). MSW incineration plants were the main source of emission for most heavy metals, HF, PCDD/-F, HCB and PCB. Further the emissions of NO_x (37 %) and SO_2 (23 %) were also considerable. Straw fired CHP plants was the main emission source for HCl. Wood fired CHP plants was the main emission source for particulates (TSP). Both wood and straw fired CHP plants were considerable emission sources for PCDD/-F. Steam turbines fuelled by residual oil was the main emission source for SO_2 and several heavy metals. Biogas fuelled engines was a considerable emission source for CO (29 %) whereas emissions of all other pollutants were low. Emissions from natural gas fuelled gas turbines and from engines fuelled by gas oil or biomass producer gas were all relatively low.

The emission of NO_x and SO_2 from decentralized CHP plants added up to 5 % of the total Danish emission. The CH_4 emission added up to 6 % of the national emission whereas the emission of several heavy metals was above 10 %. The HCB emission added up to 30 % of the national emission but it has to be taken into account that all HCB emission sources have not yet been included in the national inventory. The emission of dioxin (PCDD/-F) added up to only 1 % of the national emission whereas the emission share was approximately 35 % in 1995.

The emissions from decentralised CHP plants have been compared to the emission from Danish public electricity and heat production. The decentralized CHP plants are a major emission source for CH_4 and NMVOC. Furthermore, the decentralized CHP plants are large emission sources for NO_x, CO, heavy metals, PCDD/-F and HCB.

Suggestions for future work are included in project report 6 (Jørgensen et al., 2010c)

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List of appendices

Appendix 1 Emission factors in units of mass per Nm^3

Table A1.1 Emission factors in units of mass per Nm^3, 2006 (2007 for natural gas).

	Unit	Natural gas, engine	Biogas, engine	Natural gas, turbine	Gas oil, engine	Gas oil, turbine	Fuel oil, steam turbine	Biomass producer gas, engine	Waste	Straw	Wood
O_2	%	5	5	5	5	5	5	5	11	10	10
k_{fuel}	1000 Nm^3 per GJ	0.240	0.254	0.240	0.247	0.247	0.255	0.283	0.249	0.260	0.272
SO_2	mg per Nm^3	NE	NE	NE	NE	NE	NE	NE	16	98	4
NO_x	mg per Nm^3	429	608	151	2909	255	406	466	195	252	156
UHC	mg per Nm^3	1381	1001	7.9	NE	NE	NE	32	1.3	1.9	12
NMVOC	mg per Nm^3	291	29	5.1	NE	NE	NE	6	1.1	1.6	10
CH_4	mg per Nm^3	1529	1304	5.4	75	NE	4.0	36	0.6	0.9	5.9
CO	mg per Nm^3	185	933	15	401	8.0	8	1575	7.4	136	174
N_2O	mg per Nm^3	1.8	4.9	3.3	6.4	NE	15	7	2.4	2.3	1.6
NH_3	mg per Nm^3	NE	NE	NE	NE	NE	NE	NE	0.56	NE	NE
TSP	mg per Nm^3	NE	NE	NE	NE	NE	28	NE	0.55	4.7	19
As	µg per Nm^3	0.143	0.125	NE	0.170	NE	NE	0.312	1.133	NE	NE
Cd	µg per Nm^3	0.009	0.006	NE	0.034	NE	NE	0.024	0.84	0.65	0.52
Co	µg per Nm^3	0.65	0.63	NE	0.85	NE	NE	0.60	1.1	NE	NE
Cr	µg per Nm^3	0.15	0.55	NE	0.61	NE	NE	0.078	3.0	NE	NE
Cu	µg per Nm^3	0.047	0.94	NE	0.92	NE	NE	0.12	2.5	NE	NE
Hg	µg per Nm^3	0.31	0.38	NE	0.34	NE	NE	1.4	3.4	0.62	0.78
Mn	µg per Nm^3	0.15	0.56	NE	0.027	NE	NE	0.023	4.1	NE	NE
Ni	µg per Nm^3	0.14	0.70	NE	0.039	NE	NE	0.038	3.9	NE	NE
Pb	µg per Nm^3	0.14	0.014	NE	0.46	NE	NE	0.059	11	NE	NE
Sb	µg per Nm^3	0.16	0.38	NE	0.17	NE	NE	0.12	2.2	NE	NE
Se	µg per Nm^3	0.03	0.63	NE	0.68	NE	NE	0.48	2.1	NE	NE
Sn	µg per Nm^3	NE	NE	NE	NE	NE	NE	NE	2.0	NE	NE
Tl	µg per Nm^3	0.62	0.63	NE	0.68	NE	NE	0.48	0.85	NE	NE
V	µg per Nm^3	0.15	0.13	NE	0.020	NE	NE	0.12	0.62	NE	NE
Zn	µg per Nm^3	9.3	12	NE	179	NE	NE	0.16	4.5	0.82	4.5
PCDD/-F	pg per Nm^3	1.8	2.9	NE	3.1	NE	NE	4.7	9.5	39	28
PBDD/-F	pg per Nm^3	NE	15	NE	NE	NE	NE	19	12	NE	NE
PAH (BaP)	ng per Nm^3	41	13	NE	100	NE	NE	13	4	251	25
ΣPAH	ng per Nm^3	3256	1821	NE	27751	NE	NE	487	71	11992	1277
Naphthalene	ng per Nm^3	7791	13753	NE	54468	NE	NE	22833	246	24380	4449
HCB	ng per Nm^3	NE	0.58	NE	0.66	NE	NE	2.2	8.2	0.23	NE
PCBs	pg per Nm^3	NE	0.58	NE	0.41	NE	NE	0.64	0.61	NE	NE
Formaldehyde	mg per Nm^3	45	26	NE	4.0	NE	0.006	4.1	NE	NE	NE
Acetaldehyde	mg per Nm^3	3.2	0.35	NE	1.2	NE	0.0037	1.5	NE	NE	NE
Acrolein	mg per Nm^3	0.050	0.0032	NE	0.0054	NE	0.0037	0.0030	NE	NE	NE
Propanal	mg per Nm^3	0.25	0.068	NE	0.14	NE	0.0037	0.13	NE	NE	NE
Acetone	mg per Nm^3	1.4	0.070	NE	0.25	NE	0.012	1.5	NE	NE	NE
Butanal	mg per Nm^3	0.23	0.0032	NE	0.17	NE	0.0037	0.0030	NE	NE	NE
Pentanal	mg per Nm^3	0.038	0.0037	NE	0.021	NE	0.0037	0.0030	NE	NE	NE
Hexanal	mg per Nm^3	0.020	0.0033	NE	0.0054	NE	0.0037	0.0030	NE	NE	NE
Benzaldehyde	mg per Nm^3	0.006	0.038	NE	0.089	NE	0.0037	0.39	NE	NE	NE
Odour	OU per m^3	3904	NE	NE	NE	NE	NE	NE	NE	NE	NE
Efficiency	%	39.6	NE	28.4	NE	NE	NE	NE	NE	NE	NE
HCl	mg per Nm^3	NE	NE	NE	NE	NE	NE	NE	2.2	112	NE
HF	mg per Nm^3	NE	NE	NE	NE	NE	NE	NE	0.26	NE	NE

Appendix 2 Waste incineration plants

Table A2.1 List of waste incineration plants.

Company name	Plant name	Name of unit	MW_e	Flue gas cleaning	SNCR
Affaldsselskabet Vendsyssel Vest I/S	AVV-Forbrændingsanlæg	1 stk af 6 ton/h-ovn	4.6	DRY+FB	-
DONG Energy Generation A/S	DONG Energy Generation A/S,Odense Kraftvarmeværk A/S	ODV Odense Kraftvarme Affaldsforbrænding, 11 og 12		ESP+WET+FB	-
DONG Energy Generation A/S	DONG Energy Generation A/S,Odense Kraftvarmeværk A/S	ODV Odense Kraftvarme Affaldsforbrænding, 13	24	FB+WET	+
Energi E2 A/S	Slagelse Kraftvarmeværk	SLV	12	SD+CYK+FB	-
Energigruppen Jylland Forbrænding A/S	EnergiGruppen Jylland, Forbrændning A/S	Knudmoseværket	4	ESP+WET	-
Frederikshavn Affaldskraftvarmeværk A/S	Frederikshavn Affaldskraftvarmeværk A/S	FAV	2.5	ESP+WET	-
Haderslev Kraftvarmeværk A/S	Haderslev Kraftvarmeværk A/S	HAV	4.5	FB+WET	-
Horsens Kraftvarmeværk A/S	Horsens Kraftvarmeværk A/S	HOV (2 Affaldskedler, 1 Dampturbin)	35	DRY+FB	-
I/S Amagerforbrænding	Amager Forbrænding	4 ovne +Turbine 1 + Turbine 2	28.5	SD+FB	+
I/S Fasan	Næstved Kraftvarmeværk	NKV	7.7	SD+FB	+
I/S KARA	I/S KARA Forbrændingsanlæg	Anlæg 5	13.7	ESP+WET+FB	+
I/S Kraftvarmeværk Thisted	I/S Kraftvarmeværk Thisted	I/S E.V.A	2.92	ESP+WET	-
I/S Nordforbrænding	I/S Nordforbrænding	Ovn 4	7.4	ESP+WET+FB	+
I/S Refa	AffaldsForbrændingsanlæg I/S REFA	Linie 3	6.7	SD+CYK+FB	-
I/S Reno Nord	I/S Reno Nord	ovnlinie 4	17.9	ESP+WET	+
I/S Reno Syd	I/S Reno Syd	Kraftvarmeanlæg	2.85	ESP+WET+FB	-
I/S Vestforbrænding	I/S Vestforbrænding	Anlæg 5	17	ESP+WET+FB	+
I/S Vestforbrænding	I/S Vestforbrænding	Anlæg 6	22	FB+WET	+
I/S Aars Varmeværk	Aars Fjernvarmeforsyning	Forbrændingen, ovn 2	2.89	DRY+FB	-
Kommunekemi A/S	Kommunekemi A/S	Forbrændingsanlæg 1	7	ESP+WET+FB	-
Kommunekemi A/S	Kommunekemi A/S	Forbrændingsanlæg 3	5	ESP+WET+FB	-
Kommunekemi A/S	Kommunekemi A/S	Forbrændingsanlæg 4	5	ESP+WET+FB	-
L 90 (Leverandørforeningen af 1990)	L-90 Affaldskraftvarme Esbjerg	L90, Affaldskraftvarme Esbjerg	18	FB+WET	+
Maabjergværket A/S	Maabjergværket A/S	MBV	28	ESP+WET	+
Svendborg Kommune	Svendborg Kraftvarmeværk	Affaldsovn 1	4.5	ESP+WET	-
Sønderborg Kraftvarmeværk I/S	Sønderborg Kraftvarme I/S	Sønderborg KV	58	ESP+WET	-
TAS, Trekantomraadets Affaldsselskab I/S	Kolding Forbrændingsanlæg	Ovn linie 2	6.26	DRY+FB	-
Vejen Kraftvarmeværk A/S	Vejen Kraftvarmeværk A/S	VEV	2.5	DRY+FB	-
Aarhus Kommunaleværker, Affaldskontoret	Affaldscenter Aarhus, Forbrændingsanlægget	Ovnlinie 1+2 samt dampturbine	9	SD+FB	+
Aarhus Kommunaleværker, Affaldskontoret	Affaldscenter Aarhus, Forbrændingsanlægget	Ovnlinie 4	11.3	FB+WET	+

DRY: Dry desulphurisation, WET: Wet desulphurisation, SD: Semi-dry desulphurisation, ESP: Electrostatic precipitator, FB: Filter bag, CYK: Cyclone

Appendix 3 Emission factors for waste incineration plants

	Unit	Emission factor	Min	Max	St. dev.	Number of measurements	Measurements below the detection limit	Number of plants with measurements	Degree of coverage	Based on 0.5 x detection limit	Based on 0 x detection limit	Emission factor, year 2000
SO_2	g per GJ	8.3	0.2	29.2	10.9	43	11	7	30 %	8.2	8.2	24
NO_x	g per GJ	102	77	140	20	46	0	8	30 %	102	102	124
UHC	g per GJ	0.68	0.33	1.11	0.33	52	46	9	33 %	0.44	0.20	1.2
NMVOC	g per GJ	0.56	0.27	0.93	0.27	52	46	9	33 %	0.36	0.16	1.00
CH_4	g per GJ	0.34	0.16	0.56	0.16	52	46	9	33 %	0.22	0.10	0.60
CO	g per GJ	3.9	1.0	21.3	5.8	61	10	11	44 %	3.8	3.7	8
N_2O	g per GJ	1.2	0.4	2.8	1.4	3	0	3	13 %	1.2	1.2	1.2
NH_3	g per GJ	0.29	0.01	1.10	0.42	30	8	13	46 %	0.27	0.25	NE
TSP	g per GJ	0.29	0.02	0.57	0.19	61	12	12	46 %	0.28	0.28	2.02
As	mg per GJ	0.59	0.04	2.65	0.70	85	55	18	59 %	0.42	0.25	6.8
Cd	mg per GJ	0.44	0.00	1.05	0.46	85	57	18	59 %	0.32	0.21	4.8
Co	mg per GJ	0.56	0.12	2.31	0.53	81	78	18	59 %	0.34	0.11	2.1
Cr	mg per GJ	1.56	0.19	8.12	2.07	85	37	18	59 %	1.37	1.18	2.5
Cu	mg per GJ	1.30	0.26	4.62	1.12	85	33	18	59 %	1.20	1.10	10.1
Hg	mg per GJ	1.79	0.10	4.45	1.08	91	40	18	59 %	1.75	1.71	7.4
Mn	mg per GJ	2.14	0.01	14.04	3.26	85	32	18	59 %	2.05	1.95	3.4
Ni	mg per GJ	2.06	0.04	10.08	2.62	85	37	18	59 %	1.65	1.24	4.8
Pb	mg per GJ	5.52	0.22	28.81	6.62	85	19	18	59 %	5.48	5.44	123
Sb	mg per GJ	1.14	0.01	5.50	1.58	85	49	18	59 %	0.96	0.79	23
Se	mg per GJ	1.11	0.16	4.71	1.45	26	24	9	36 %	0.56	0.02	1.6
Sn	mg per GJ	1.05	-	-	-	1	1	1	13 %	0.52	0.00	-
Tl	mg per GJ	0.45	0.03	1.05	0.36	85	85	18	59 %	0.22	0.00	2.5
V	mg per GJ	0.33	0.02	1.05	0.41	85	78	18	59 %	0.17	0.01	2.5
Zn	mg per GJ	2.33	0.18	14.52	4.65	26	0	9	36 %	2.33	2.33	359.5[1)]
PCDD/-F	ng per GJ	5.0	0.6	12.9	3.9	77	8	18	59 %	4.6	4.2	157
PBDD/-F	ng per GJ	6.3	6.0	6.8	0.6	2	2	2	8 %	6	6	NE
PAH (BaP)	µg per GJ	2.2	1.9	2.4	0.3	3	3	3	13 %	1.4	0.5	6
ΣPAH	µg per GJ	37	21	49	16	3	3	3	13 %	33	28	NE
Naphthalene	µg per GJ	129	100	162	34	3	3	3	13 %	64	0	3405
HCB	µg per GJ	4.3	0.2	10.5	5.9	3	2	3	13 %	4.2	4.2	NE
PCB	ng per GJ	0.32	0.16	0.53	0.21	3	3	3	13 %	0.16	0.00	NE
HCl	g per GJ	1.1	0.2	3.0	1.1	48	14	8	32 %	1.0	0.9	4.4
HF	g per GJ	0.14	0.05	0.58	0.19	77	68	15	45 %	0.07	0.01	0.3

1. Not a part of the previous emission factor project. NE: Not Estimated

Appendix 4 Emission factors for straw fired plants

Pollutant	Unit	Emis-sion factor	Min	Max	St. dev.	Number of measure-ments	Measurements below detection limit	Number of plants with measurements	Degree of coverage	Emission factor, year 2000
SO_2	g per GJ	49	24	78	20	15	0	5	83%	47
NO_x	g per GJ	125	98	178	32	14	0	5	83%	131
UHC	g per GJ	0.94	0.8	1.0	0.1	7	6	4	65%	0.93
CO	g per GJ	67	28	145	46	16	0	6	100%	63
N_2O	g per GJ	1.1	0.8	1.9	0.62	6	0	3	48%	1.4
TSP	g per GJ	2.3	0.1	7	3	13	2	5	85%	3.97
Cd	mg per GJ	0.32	0.002	0.69	0.38	7	7	4	68%	0.8
Hg	mg per GJ	0.31	0.10	0.57	0.25	7	7	4	68%	0.6
Zn	mg per GJ	0.41	0.40	0.43	0.02	2	0	2	35%	-
PCDD/-F	ng per GJ	19	1.0	97	42	9	2	5	85%	22
PAH (BaP)	µg per GJ	125	6	440	307	6	2	3	48%	154
ΣPAH	µg per GJ	5946	173	180	4	2	2	2	48%	-
Naphthalene	µg per GJ	12088	1238	40468	22378	6	0	3	48%	15200
HCl	g per GJ	56	24	75	20	8	0	5	83%	46
HCB	µg per GJ	0.11	0.10	0.15	0.04	2	1	2	35%	-

Appendix 5 Emission factors for wood fired plants

Pollutant	Unit	Emission factor	Min	Max	St. dev.	Number of measure-ments	Measurements below detection limit	Number of plants with measurements	Degree of coverage	Emission factor, year 2000
SO2	g per GJ	1.9	1	12	8	4	1	2	42 %	1.74
NOx	g per GJ	81	77	92	10	5	0	2	42 %	69
UHC	g per GJ	6.1	2	40	27	3	2	2	42 %	4.0
CO	g per GJ	90	51	201	106	6	0	2	42 %	79
N2O	g per GJ	0.8	2	2	0	2	0	1	31 %	0.8
TSP	g per GJ	10	3	29	18	6	0	2	42 %	7.94
Cd	mg per GJ	0.27	0	2	1	3	1	2	42 %	0.9
Hg	mg per GJ	0.40	0	2	2	3	3	2	42 %	0.72
Zn	mg per GJ	2.3	5	5	0	1	0	1	31 %	-
PCDD/-F	ng per GJ	14	4	36	23	3	1	2	42 %	1
PAH (BaP)	µg per GJ	13	8	31	17	3	2	2	42 %	8
ΣPAH	µg per GJ	664	-	-	-	-	-	-	-	-
Naphthalene	µg per GJ	2314	879	5717	3421	3	0	2	42 %	2071

Appendix 6 Emission factors for natural gas powered engines

Table A.6.1 Emission factors for natural gas powered engines, 2007.

Pollutant	Unit	Emission factor (Full load)	Min	Max	St. dev.	Number of measure-ments	Emission factor year 2000
NO_x	g per GJ	135	11	285	34	157	168
UHC	g per GJ	421	11	1200	168	157	485
NMVOC	g per GJ	89	2	253	36	157	117
CH_4	g per GJ	466	12	1329	187	157	520
CO	g per GJ	56	2	240	34	157	175
N_2O	g per GJ	0.6	0.4	0.8	0.1	10	1.3
As	mg per GJ	0.05	0.01	0.05	0.03	2	-
Cd	mg per GJ	0.003	0.00	0.01	0.00	2	-
Co	mg per GJ	0.20	0.20	0.24	0.03	2	-
Cr	mg per GJ	0.05	0.02	0.25	0.16	2	-
Cu	mg per GJ	0.01	0.00	0.10	0.06	2	-
Hg	mg per GJ	0.10	0.09	0.10	0.01	2	-
Mn	mg per GJ	0.05	0.01	0.05	0.03	2	-
Ni	mg per GJ	0.05	0.03	0.15	0.08	2	-
Pb	mg per GJ	0.04	0.04	0.04	0.00	2	-
Sb	mg per GJ	0.05	0.04	0.05	0.00	2	-
Se	mg per GJ	0.20	0.18	0.20	0.02	2	-
Tl	mg per GJ	0.20	0.18	0.20	0.02	2	-
V	mg per GJ	0.05	0.03	0.05	0.01	2	-
Zn	mg per GJ	2.9	1.14	3.14	1.42	2	-
PCDD/-F	ng per GJ	0.57	0.5	1.1	0.4	2	-
PAH BaP	µg per GJ	13	4	14	7	2	23
ΣPAH	µg per GJ	1025	47	1150	780	2	-
Naphthalene	µg per GJ	2452	184	2743	1809	2	7900
Formaldehyde	g per GJ	14.1	0.3	39.7	9.44	32	24
Acetaldehyde	g per GJ	1.01	0.00	1.86	0.47	12	1.88
Acrolein	g per GJ	0.016	0.001	0.220	0.076	11	0.09
Propanal	g per GJ	0.078	0.003	0.101	0.031	12	0.17
Acetone	g per GJ	0.45	0.01	0.72	0.24	12	0.22
Butanal	g per GJ	0.071	0.001	0.094	0.031	9	0.10
Pentanal	g per GJ	0.012	0.001	0.069	0.030	6	0.13
Hexanal	g per GJ	0.0063	0.0012	0.066	0.027	7	0.02
Benzaldehyde	g per GJ	0.0019	0.0003	0.012	0.005	8	0.03
Odour	OU per m3	3904	1800	12050	3514	6	8229
Efficiency	%	39.6	31.3	46.3	2.89	144	38.3

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Table A.6.2 Emission factors for natural gas powered engines based on measurements 2003-2006.

2003-2006	Unit	Emission factor (Full load)	Min	Max	St. dev.	Number of measurements
NO_x	g per GJ	143	6	353	46	368
UHC	g per GJ	406	5	1067	171	366
NMVOC	g per GJ	86	1	225	36	366
CH_4	g per GJ	450	6	1181	189	366
CO	g per GJ	77	2	285	71	368
Formaldehyde [1)]	g per GJ	14.1	0.3	39.7	9.44	32
Acetaldehyde [1)]	g per GJ	1.01	0.00	1.86	0.47	12
Acrolein [1)]	g per GJ	0.016	0.001	0.220	0.076	11
Propanal [1)]	g per GJ	0.078	0.003	0.101	0.031	12
Acetone [1)]	g per GJ	0.45	0.01	0.72	0.24	12
Butanal [1)]	g per GJ	0.071	0.001	0.094	0.031	9
Pentanal [1)]	g per GJ	0.012	0.001	0.069	0.030	6
Hexanal [1)]	g per GJ	0.0063	0.0012	0.066	0.027	7
Benzaldehyde [1)]	g per GJ	0.0019	0.0003	0.012	0.005	8
Odour	OU per m^3	7809	1150	17200	4974	15
Efficiency	%	39.4	32.2	44.7	2.5	352

[1)] Based on measurements from 2003-2009.

Appendix 7 Emission factors for biogas powered engines

Pollutant	Unit	Emission factor (Full load)	Min	Max	St. dev.	Number of measure-ments	Emission factor year 2000
NO_x	g per GJ	202	109	367	89	10	540
UHC	g per GJ	333	121	626	170	10	254
NMVOC	g per GJ	10	3	18	5	10	14
CH_4	g per GJ	434	158	816	221	10	323
CO	g per GJ	310	51	432	114	10	273
N_2O	g per GJ	1.6	1.5	2.1	0.3	3	0.5
As	mg per GJ	0.04	-	-	-	1	-
Cd	mg per GJ	0.002	-	-	-	1	-
Co	mg per GJ	0.21	-	-	-	1	-
Cr	mg per GJ	0.18	-	-	-	1	-
Cu	mg per GJ	0.31	-	-	-	1	-
Hg	mg per GJ	0.12	-	-	-	1	-
Mn	mg per GJ	0.19	-	-	-	1	-
Ni	mg per GJ	0.23	-	-	-	1	-
Pb	mg per GJ	0.005	-	-	-	1	-
Sb	mg per GJ	0.12	-	-	-	1	-
Se	mg per GJ	0.21	-	-	-	1	-
Tl	mg per GJ	0.21	-	-	-	1	-
V	mg per GJ	0.04	-	-	-	1	-
Zn	mg per GJ	3.95	-	-	-	1	-
PCDD/-F	ng per GJ	0.96	-	-	-	1	-
PBDD/-F	ng per GJ	5.0	-	-	-	1	-
PAH (BaP)	µg per GJ	4.2	-	-	-	1	3
ΣPAH	µg per GJ	606	-	-	-	1	
Naphthalene	µg per GJ	4577	-	-	-	1	3300
HCB	µg per GJ	0.19	-	-	-	1	-
PCB	ng per GJ	0.19	-	-	-	1	-
Formaldehyde	g per GJ	8.7	6.4	20	6.6	3	21
Acetaldehyde	g per GJ	0.116	0.051	0.453	0.213	3	0.11
Acrolein	g per GJ	0.001	0.001	0.001	0.000	3	0.01
Propanal	g per GJ	0.023	0.001	0.107	0.059	3	0.003
Acetone	g per GJ	0.023	0.009	0.079	0.040	3	0.025
Butanal	g per GJ	0.001	0.001	0.001	0.000	3	0.004
Pentanal	g per GJ	0.001	0.001	0.004	0.001	3	0
Hexanal	g per GJ	0.001	0.001	0.001	0.000	3	0
Benzaldehyde	g per GJ	0.013	0.006	0.028	0.011	3	0.002

Appendix 8 Emission factors for natural gas powered gas turbines

Table A8.1 Emission factors for natural gas powered gas turbines, 2007.

	Unit	Emission factor	Min	Max	St. dev.	Number of measurements	Emission factor year 2000
NO_x	g per GJ	48	36	60	10	7	124
UHC	g per GJ	2.5	2	14	5	5	2.3
NMVOC	g per GJ	1.6	1.4	9.3	3.0	5	
CH_4	g per GJ	1.7	1.5	10.0	3.2	5	
CO	g per GJ	4.8	1	86	31	7	6
N_2O	g per GJ	1.0	0.7	1.2	0.3	3	2.2
Efficiency	%	28.4	25	30.2	2.4	4	28.8

Table A8.2 Emission factors for natural gas powered gas turbines based on measurements 2003-2006.

	Unit	Emission factor	Min	Max	St. dev.	Number of measurements
NO_x	g per GJ	98	38	224	56	22
UHC	g per GJ	2.5	2.2	14.5	4.6	5
NMVOC	g per GJ	1.6	1.4	9.3	3.0	5
CH_4	g per GJ	1.7	1.5	10	3.2	5
CO	g per GJ	6.2	2.8	122	42	22
Efficiency	%	28.8	26.3	31.5	1.3	22

Appendix 9 Emission factors for gas oil powered engines

	Unit	Emission factor	Min	Max	St. dev.	Number of measurements	Previously used emission factor
NO_x	g per GJ	942	632	1369	219	17	700
UHC	g per GJ	18	4	24	5	12	
NMVOC	g per GJ	-	-	-	-	0	100
CH_4	g per GJ	24	6	32	7	12	1.5
CO	g per GJ	130	33	269	52	17	100
N_2O	g per GJ	2.1	1.4	5.9	3.1	2	2
As	mg per GJ	0.06	-	-	-	1	1.17
Cd	mg per GJ	0.01	-	-	-	1	0.23
Co	mg per GJ	0.28	-	-	-	1	-
Cr	mg per GJ	0.20	-	-	-	1	0.94
Cu	mg per GJ	0.30	-	-	-	1	1.17
Hg	mg per GJ	0.11	-	-	-	1	1.17
Mn	mg per GJ	0.01	-	-	-	1	-
Ni	mg per GJ	0.01	-	-	-	1	0.64
Pb	mg per GJ	0.15	-	-	-	1	2.34
Sb	mg per GJ	0.06	-	-	-	1	-
Se	mg per GJ	0.22	-	-	-	1	4.68
Tl	mg per GJ	0.22	-	-	-	1	-
V	mg per GJ	0.01	-	-	-	1	-
Zn	mg per GJ	58	-	-	-	1	11.7
PCDD/-F	ng per GJ	0.99	-	-	-	1	0.882
PAH (BaP)	µg per GJ	33	-	-	-	1	
ΣPAH	µg per GJ	8988	-	-	-	1	
Naphthalene	µg per GJ	17642	-	-	-	1	
HCB	µg per GJ	0.22	-	-	-	1	
PCBs	ng per GJ	0.13	-	-	-	1	
Formaldehyde	g per GJ	1.3	1.0	3.3	1.6	2	
Acetaldehyde	g per GJ	0.404	0.221	1.470	0.884	2	
Acrolein	g per GJ	0.002	0.002	0.002	0.000	2	
Propanal	g per GJ	0.045	0.024	0.170	0.104	2	
Acetone	g per GJ	0.082	0.006	0.525	0.367	2	
Butanal	g per GJ	0.055	0.002	0.363	0.255	2	
Pentanal	g per GJ	0.007	0.002	0.037	0.025	2	
Hexanal	g per GJ	0.002	0.002	0.002	0.000	2	
Benzaldehyde	g per GJ	0.029	0.002	0.186	0.130	2	

Appendix 10 Emission factors for engines combusting biomass producer gas

Table A10.1 Emission factors for engines combusting biomass producer gas.

	Unit	Emission factor	Min	Max	St. dev.	Number of plants with measurements
NO_x	g per GJ	173	173	295	86	2
UHC	g per GJ	12	12	30	13	2
NMVOC	g per GJ	2	-	-	-	2
CH_4	g per GJ	13	-	-	-	2
CO	g per GJ	586	585	696	79	2
N_2O	g per GJ	2.7	-	-	-	1
As	mg per GJ	0.12	-	-	-	1
Cd	mg per GJ	0.009	-	-	-	1
Co	mg per GJ	0.22	-	-	-	1
Cr	mg per GJ	0.029	-	-	-	1
Cu	mg per GJ	0.045	-	-	-	1
Hg	mg per GJ	0.54	-	-	-	1
Mn	mg per GJ	0.008	-	-	-	1
Ni	mg per GJ	0.014	-	-	-	1
Pb	mg per GJ	0.022	-	-	-	1
Sb	mg per GJ	0.045	-	-	-	1
Se	mg per GJ	0.18	-	-	-	1
Tl	mg per GJ	0.18	-	-	-	1
V	mg per GJ	0.045	-	-	-	1
Zn	mg per GJ	0.058	-	-	-	1
PCDD/-F	ng per GJ	1.7	-	-	-	1
PBDD/-F	ng per GJ	7.2	-	-	-	1
PAH (BaP)	µg per GJ	4.9	-	-	-	1
ΣPAH	µg per GJ	181	-	-	-	1
Naphthalen	µg per GJ	8492	-	-	-	1
HCB	µg per GJ	0.80	-	-	-	1
PCB	ng per GJ	0.24	-	-	-	1
Formaldehyde	g per GJ	1.5	-	-	-	1
Acetaldehyde	g per GJ	0.56	-	-	-	1
Acrolein	g per GJ	0.001	-	-	-	1
Propanal	g per GJ	0.048	-	-	-	1
Acetone	g per GJ	0.56	-	-	-	1
Butanal	g per GJ	0.001	-	-	-	1
Pentanal	g per GJ	0.001	-	-	-	1
Hexanal	g per GJ	0.001	-	-	-	1
Benzaldehyde	g per GJ	0.14	-	-	-	1

Appendix 11 Emission factors for PCDD/-F, PBDD/-F, PAH and PCB

Table A11.1 Emission factors for PCDD/-F, all plant types.

	Unit	Gas oil, engine	Biomass producer gas, engine	Biogas, engine	Natural gas, engine	Waste[1)]	Straw	Wood	Toxic equivalence factor[2]
PCDD/-F [1)]	ng per GJ	0.99	1.7	0.96	0.57	2.8	0.73	36	-
2,3,7,8-TCDD	ng per GJ	0.20	0.36	0.22	0.12	0.30	0.15	9.0	1
1,2,3,7,8-PeCDD	ng per GJ	0.27	0.47	0.29	0.15	0.48	0.20	5.9	0.5
1,2,3,4,7,8,-HxCDD	ng per GJ	0.53	0.95	0.58	0.31	0.88	0.40	2.3	0.1
1,2,3,6,7,8-HxCDD	ng per GJ	0.53	0.95	0.58	0.31	2.3	0.40	3.5	0.1
1,2,3,7,8,9-HxCDD	ng per GJ	0.53	0.95	0.58	0.31	1.3	0.40	2.6	0.1
1,2,3,4,6,7,8-HpCDD	ng per GJ	0.60	0.67	0.41	0.39	15	0.59	10	0.01
OCDD	ng per GJ	2.2	1.9	1.2	1.8	18	0.96	7	0.001
2,3,7,8-TCDF	ng per GJ	0.35	0.63	0.38	0.20	0.89	0.26	113	0.1
1,2,3,7,8-PeCDF	ng per GJ	0.48	0.85	0.52	0.28	1.7	0.36	14	0.05
2,3,4,7,8-PeCDF	ng per GJ	0.48	0.85	0.52	0.28	1.5	0.36	19	0.5
1,2,3,4,7,8-HxCDF	ng per GJ	0.45	0.79	0.48	0.26	2.1	0.33	4.87	0.1
1,2,3,6,7,8-HxCDF	ng per GJ	0.45	0.79	0.48	0.26	2.0	0.33	3.9	0.1
1,2,3,7,8,9-HxCDF	ng per GJ	0.45	0.79	0.48	0.26	0.51	0.33	0.46	0.1
2,3,4,6,7,8-HxCDF	ng per GJ	0.45	0.79	0.48	0.26	2.0	0.33	5.1	0.1
1,2,3,4,6,7,8-HpCDF	ng per GJ	0.54	0.75	0.46	0.24	5.6	0.32	3.1	0.01
1,2,3,4,7,8,9-HpCDF	ng per GJ	0.42	0.75	0.46	0.24	0.80	0.31	0.99	0.01
OCDF	ng per GJ	2.1	3.7	2.3	1.2	3.0	1.6	2.2	0.001

[1)] Includes only project measurements. Data for single congeners are not available for the existing measurement reports. Data for total PCDD/-F in this table deviates from the emission factor calculated based on all data sets.
[2)] Based on executive order no.162.

Table A11.2 Emission factors for PBDD/-F, all plant types.

	Unit	Waste	Biomass producer gas, engine	Biogas, engine	Toxic equivalence factor[1]
PBDD/-F [1)]	ng per GJ	< 6.3	< 7.2	< 5.0	-
2,3,7,8,-TBDF	ng per GJ	< 0.23	< 0.39	< 0.24	0.1
1,2,3,7,8-PeBDF	ng per GJ	< 0.77	< 1.6	< 0.96	0.05
2,3,4,7,8-PeBDF	ng per GJ	< 0.77	< 1.6	< 0.96	0.5
1,2,3,4,7,8/1,2,3,6,7,8-HxBDF	ng per GJ	< 1.5	< 1.6	< 0.96	0.1
2,3,4,6,7,8-HxBDF	ng per GJ	< 1.5	< 1.6	< 0.96	0.1
1,2,3,7,8,9-HxBDF	ng per GJ	< 1.5	< 1.6	< 0.96	0.1
1,2,3,4,6,7,8-HpBDF	ng per GJ	< 25	< 39	< 24	0.01
1,2,3,4,7,8,9-HpBDF	ng per GJ	< 25	< 39	< 24	0.01
OBDF	ng per GJ	< 376	< 592	< 360	0.001
2,3,7,8-TBDD	ng per GJ	< 0.20	< 0.16	< 0.10	1
1,2,3,7,8-PeBDD	ng per GJ	< 2.5	< 4	< 2.4	0.5
1,2,3,4,7,8/1,2,3,6,7,8-HxBDD	ng per GJ	< 7.7	< 12	< 7.2	0.1
1,2,3,7,8,9-HxBDD	ng per GJ	< 7.7	< 12	< 7.2	0.1
1,2,3,4,6,7,8-HpBDD	ng per GJ	< 7.7	< 12	< 7.2	0.01
OBDD	ng per GJ	< 7.7	< 13	< 7.2	0.001

[1)] Based on executive order no. 162 (DEPA 2003) for PCDD/-F.

Table A11.3 Emission factors for PAH, all plant types.

	Unit	Gas oil Engine	Biomass producer gas Engine	Biogas Engine	Natural gas Engine	Waste	Straw	Wood	Toxic equivalence factor[1]
Naphthalene	µg per GJ	17 642	8492	4577	2452	129	12088	2314	-
Acenaphthylene	µg per GJ	1020	4	6	124	1.1	3.5	559	0.001
Acenaphthene	µg per GJ	295	11	70	29	5.3	1.1	9	0.001
Fluorene	µg per GJ	1926	59	87	63	5.6	4.3	36	0.0005
Phenanthrene	µg per GJ	4139	80	359	327	11	8.7	338	0.0005
Anthracene	µg per GJ	400	2.0	11	31	0.8	0.5	30	0.0005
Fluoranthene	µg per GJ	404	6	22	158	2.9	1.6	157	0.05
Pyrene	µg per GJ	647	4	20	254	2.5	1.5	193	0.001
Benz[a]anthracene	µg per GJ	45	2.0	2.5	7	0.9	0.5	10	0.005
Chrysene	µg per GJ	89	2.0	23	14	1.1	0.5	12	0.03
Benzo[b/j]fluoranthene	µg per GJ	15	2.0	1.2	9	1.7	0.5	15	0.1
Benzo[k]fluoranthene	µg per GJ	1.7	2.0	1.2	1.7	0.9	0.5	5	0.05
Benzo[a]pyrene	µg per GJ	1.9	2.0	1.3	1.2	0.8	0.5	11	1
Dibenz[a,h]anthracene	µg per GJ	0.7	2.0	0.5	1.2	0.8	0.5	0.8	1.1
Indeno[123-cd]pyrene	µg per GJ	1.5	2.0	0.6	1.8	1.1	0.5	10	0.1
Benzo[ghi]perylene	µg per GJ	2.3	2.0	0.6	2.7	1.1	0.5	13	0.01
PAH (BaP)	µg per GJ	33	4.9	4.2	13	12	1.3	24	-
ΣPAH	µg per GJ	8988	181	606	1025	37	25	1398	-

[1)] DEPA, 2001.

Table A11.4 Emission factors for PCB, all plant types.

	Unit	Gas oil, engine	Biomass producer gas, engine	Biogas, engine	Waste	Toxic equivalence factor[1)]
PCB 77	ng per GJ	< 3	< 5	< 3	< 3	0.0001
PCB 81	ng per GJ	< 0.5	< 0.9	< 0.5	< 1	0.0003
PCB 105	ng per GJ	< 13	< 23	< 14	< 15	0.00003
PCB 114	ng per GJ	< 2	< 4	< 2	< 2	0.00003
PCB 118	ng per GJ	< 47	< 83	< 50	< 53	0.00003
PCB 123	ng per GJ	< 2	< 4	< 2	< 2	0.00003
PCB 126	ng per GJ	< 0.7	< 1.2	< 1.0	< 2	0.1
PCB 156	ng per GJ	< 9	< 15	< 10	< 10	0.00003
PCB 157	ng per GJ	< 4	< 7	< 4	< 5	0.00003
PCB 167	ng per GJ	< 5	< 9	< 6	< 6	0.00003
PCB 169	ng per GJ	< 3	< 5	< 3	< 3	0.03
PCB 189	ng per GJ	< 4	< 7	< 4	< 5	0.00003
PCB sum [1)]	ng per GJ	< 0.13	< 0.24	< 0.19	< 0.32	-

[1)] WHO, 2005.

Appendix 12 Degree of coverage

Table A12.1 Degree of coverage.

	Natural gas, engines, %	Biogas, engines, %	Natural gas, turbines, %	Gas oil, gas engines, %	Gas oil, gas turbines, %	Fuel oil, steam turbines, %	Biomass producer gas, engines, %	Waste, %	Straw, %	Wood, %
SO_2	-	-	-	-	-	-	-	30	83	42
NO_x	38	8	31	73	NE	64	100	30	83	42
UHC (C)	38	8	NE	27	-	64	100	33	65	42
NMVOC	38	8	NE	-	-	-	100	33	65	42
CH_4	38	8	NE	27	-	64	100	33	65	42
CO	38	8	31	73	NE	64	100	44	100	42
N_2O	8	3	17	8	-	64	100	13	48	31
NH_3	-	-	-	-	-	-	-	46	-	-
TSP	-	-	-	-	-	88	-	46	85	42
As	4	3	-	27	-	-	100	59	-	-
Cd	4	3	-	27	-	-	100	59	68	42
Co	4	3	-	27	-	-	100	59	-	-
Cr	4	3	-	27	-	-	100	59	-	-
Cu	4	3	-	27	-	-	100	59	-	-
Hg	4	3	-	27	-	-	100	59	68	42
Mn	4	3	-	27	-	-	100	59	-	-
Ni	4	3	-	27	-	-	100	59	-	-
Pb	4	3	-	27	-	-	100	59	-	-
Sb	4	3	-	27	-	-	100	59	-	-
Se	4	3	-	27	-	-	100	36	-	-
Sn	-	-	-	-	-	-	-	13	-	-
Tl	4	3	-	27	-	-	100	59	-	-
V	4	3	-	27	-	-	100	59	-	-
Zn	4	3	-	27	-	-	100	36	35	31
PCDD/-F	4	3	-	27	-	-	100	59	85	42
PBDD/-F	-	3	-	-	-	-	100	8	-	-
PAH (BaP)	4	3	-	27	-	-	100	30	48	42
ΣPAH	4	3	-	27	-	-	100	30	48	42
Naphthalene	4	3	-	27	-	-	100	13	48	42
HCB	-	3	-	27	-	-	100	13	35	-
PCB	-	3	-	27	-	-	100	13	-	-
Formaldehyde	11	3	-	8	-	64	100	-	-	-
Acetaldehyde	6	3	-	8	-	64	100	-	-	-
Acrolein	6	3	-	8	-	64	100	-	-	-
Propanal	6	3	-	8	-	64	100	-	-	-
Acetone	6	3	-	8	-	64	100	-	-	-
Butanal	6	3	-	8	-	64	100	-	-	-
Pentanal	5	3	-	8	-	64	100	-	-	-
Hexanal	5	3	-	8	-	64	100	-	-	-
Benzaldehyde	5	3	-	8	-	64	100	-	-	-
Odour	NE	-	-	-	-	-	-	-	-	-
Efficiency	NE	-	NE	-	-	-	-	-	-	-
HCl	-	-	-	-	-	-	-	32	83	-
HF	-	-	-	-	-	-	-	45	-	-

Appendix 13 Emission share of decentralised CHP for the different plant types

Table A13.1 Emission share for the different plant types.

	Natural gas, engines, %	Biogas, engines, %	Natural gas, turbines, %	Gas oil, gas engines, %	Gas oil, gas turbines, %	Fuel oil, steam turbines, %	Biomass producer gas, engines, %	Waste, %	Straw, %	Wood, %	Total Decen-tralised CHP %
Fuel con-sumption	35	4	9	0.0	0.1	3	0.1	42	4	4	100
SO_2	1	5	0	0	0	58	0	23	13	1	100
NO_x	41	7	4	0	0	3	0	37	4	3	100
UHC (C)	92	8	0	0	0	0	0	0	0	0	100
NMVOC	97	1	0	0	0	0	0	1	0	1	100
CH_4	91	9	0	0	0	0	0	0	0	0	100
CO	49	29	1	0	0	0	1	4	6	10	100
N_2O	18	6	8	0	0	13	0	47	4	3	100
NH_3	0	0	0	0	0	0	0	100	0	0	100
TSP	20	8	1	0	0	21	0	9	7	34	100
As	2	0	0	0	0	47	0	29	9	12	100
Cd	0	0	0	0	0	65	0	31	2	2	100
Co	21	2	5	0	0	0	0	71	0	0	100
Cr	1	0	0	0	0	53	0	37	3	6	100
Cu	0	1	0	0	0	33	0	49	6	10	100
Hg	4	1	1	0	0	13	0	79	1	2	100
Mn	2	1	0	0	0	0	0	97	0	0	100
Ni	0	0	0	0	0	95	0	4	0	1	100
Pb	0	0	0	0	0	20	0	68	7	5	100
Sb	3	1	1	0	0	0	0	95	0	0	100
Se	0	1	0	0	0	42	0	56	0	0	100
Sn	0	0	0	0	0	0	0	100	0	0	100
Tl	24	3	6	0	0	0	0	67	0	0	100
V	10	1	3	0	0	0	0	86	0	0	100
Zn	34	5	8	1	2	3	0	33	11	3	100
PCDD/-F	5	1	0	0	0	1	0	54	22	17	100
PBDD/-F	0	7	0	0	0	0	0	93	0	0	100
PAH (BaP)	39	1	4	0	0	0	0	8	42	5	100
ΣPAH	53	4	1	1	0	0	0	2	35	4	100
Naphthalene	50	10	2	0	0	0	0	3	28	6	100
HCB	0	0	0	0	0	0	0	90	0	9	100
PCB	0	5	0	0	0	0	0	95	0	0	100
Formaldehyde	94	8	0	0	0	0	0	0	0	0	100
Acetaldehyde	99	2	0	0	0	0	0	0	0	0	100
Acrolein	99	1	0	0	0	0	0	0	0	0	100
Propanal	97	7	0	0	0	0	0	0	0	0	100
Acetone	99	1	1	0	0	0	0	0	0	0	100
Butanal	96	0	5	0	0	0	0	0	0	0	100
Pentanal	98	1	0	0	0	0	0	0	0	0	100
Hexanal	97	5	0	0	0	4	0	0	0	0	100
Benzaldehyde	50	25	0	1	0	2	6	0	0	0	100
HCl	0	0	0	0	0	0	0	18	81	1	100
HF	0	0	0	0	0	0	0	83	11	6	100

Appendix 14 Measurement programme

Table A14.1 Measurement programme for gas and oil.

Plant no.	Plant type	Make	Model	Fuel	Standard pollutants	Special measure-ments
1	Engine	Diesel engine		Gas oil	NO_x, UHC, CH_4, NMVOC, CO, N_2O, aldehydes	PCDD/-F, PAH, metals, HCB, PCB, UFP (Ultra Fine Particles)
2	Engine	Diesel engine	Regulating reserves	Gas oil	NO_x, UHC, CH_4, NMVOC, CO, N_2O, aldehydes	
3	Steam turbine	Unknown	Unknown	Fuel oil	NO_x, UHC, CH_4, NMVOC, CO, N_2O, aldehydes	
4	Engine	Jenbacher	J 320	Biomass producer gas	NO_x, UHC, CH_4, NMVOC, CO, N_2O, aldehydes	PCDD/-F, PAH, HCB, PCB, PBDD/-F
5	Engine	Jenbacher	J 316	Biogas, landfill	NO_x, UHC, CH_4, NMVOC, CO, N_2O, aldehydes	PCDD/-F, PAH, metals, HCB, PCB, PBDD/-F, UFP
6	Engine	Jenbacher	J 208 GS-C	Biogas, manure	NO_x, UHC, CH_4, NMVOC, CO, N_2O, aldehydes	
7	Engine	MAN	E0836 LE202	Biogas, wastewater	NO_x, UHC, CH_4, NMVOC, CO, N_2O, aldehydes	
8	Engine	Rolls Royce	KVGS-18G4	Natural gas	NO_x, UHC, CH_4, NMVOC, CO, N_2O, aldehydes	PCDD/-F, PAH, metals, UFP
9	Engine	Jenbacher	JMS 316	Natural gas	NO_x, UHC, CH_4, NMVOC, CO, N_2O, aldehydes	
10	Engine	Wärtsilä	18V34SG	Natural gas	NO_x, UHC, CH_4, NMVOC, CO, N_2O, aldehydes	
11	Engine	Caterpillar	G3516	Natural gas	NO_x , UHC, CH_4, NMVOC, CO, N_2O, aldehydes	PCDD/-F, PAH, metals
12	Engine	Caterpillar	G 3612	Natural gas	NO_x, UHC, CH_4, NMVOC, CO, N_2O	
13	Engine	Jenbacher	JMS 620	Natural gas	NO_x , UHC, CH_4, NMVOC, CO, N_2O	
14	Engine	Wärtsilä	12V25SG	Natural gas	NO_x, UHC, CH_4, NMVOC, CO, N_2O	
15	Engine	Deutz MVM	TBG 604	Natural gas	NO_x, UHC, CH_4, NMVOC, CO, N_2O	
16	Engine	Rolls Royce	B35:40V-12AG	Natural gas	NO_x, UHC, CH_4, NMVOC, CO, N_2O	
17	Gas turbine	EGT	Typhoon	Natural gas	NO_x, CO, N_2O	
18	Gas turbine	EGT	Tornado	Natural gas	NO_x, CO, N_2O	
19	Gas turbine	Alstom	GT35C2	Natural gas	NO_x, CO, N_2O	

Table A14.2 Measurement programme for waste and biomass.

Plant no.	Plant type	Flue gas cleaning	Emission measurements
A1	Waste incineration	ESP+WET+FB, SNCR	TSP, As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Sb, Se, Tl, V, Zn, CO, CO_2, O_2, PCDD/-F, PBDD/-F, HCB, PCB, PAH, Naphthalene, NH_3, N_2O
A2	Waste incineration	ESP+WET, SNCR	TSP, As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Sb, Se, Tl, V, Zn, CO, CO_2, O_2, PCDD/-F, PBDD/-F, HCB, PCB, PAH, Naphthalene, NH_3, N_2O
A3	Waste incineration	SD+CYK+FB	TSP, As, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Sb, Se, Tl, V, Zn, CO, CO_2, O_2, PCDD/-F, PBDD/-F, HCB, PCB, PAH, Naphthalene, NH_3, N_2O
B1	Biomass, straw	FB	TSP, Cd, Hg, Zn, CO, CO_2, O_2, PCDD/-F, HCB, PAH, Naphthalene, TOC, NO_x, SO_2, HCl, N_2O
B2	Biomass, straw	FB	TSP, Cd, Hg, Zn, CO, CO_2, O_2, PCDD/-F, HCB, PAH, Naphthalene, TOC, NO_x, SO_2, HCl, N_2O
B3	Biomass, wood	ESP	TSP, Cd, Hg, Zn, CO, CO_2, O_2, PCDD/-F, PAH, Naphthalene, TOC, NO_x, N_2O

ESP: Electrostatic precipitator, WET: Wet desulphurisation, FB: Filter bag, SNCR: Selective non-catalytic reduction, SD: Semi-dry desulphurisation, CYK: Cyclone.

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EMISSIONS FROM DECENTRALISED CHP PLANTS 2007 - ENERGINET.DK ENVIRONMENTAL PROJECT NO. 07/1882

Project report 5 – Emission factors and emission inventory for decentralised CHP production

Updated emission factors for decentralised combined heat and power (CHP) plants with a capacity < 25MWe have been estimated based on project emission measurements as well as emission measurements performed in recent years that were collected. The emission factors valid for 2006/2007 have been estimated for the plant technologies: Municipal solid waste (MSW) incineration plants, plants combusting straw or wood, natural gas fuelled reciprocating engines, biogas fuelled engines, natural gas fuelled gas turbines, gas oil fuelled reciprocating engines, gas oil fuelled gas turbines, steam turbines combusting residual oil and reciprocating engines combusting biomass producer gas based on wood.

The emission factors for MSW in-cineration plants are much lower than the emission factors that were estimated for year 2000. The considerable reduction in the emission factors is a result of lower emission limit values in Danish legislation since 2006 that has lead to installation of new and improved flue gas cleaning systems in most MSW incineration plants. For CHP plants combusting wood or straw no major technical improvements have been implemented.

The emission factors for natural gas fuelled reciprocating engines have been reduced since year 2000 as a result of technical improvements that have been carried out due to lower emission limit values in Danish legislation. The NO_x emission factor for natural gas fuelled gas turbines has decreased 62 % since year 2000. This is a result of installation of low-NO_x burners in almost all gas turbines that has been necessary to meet new emission limits in Danish legislation. The emission measurements programme included screening of the emissions of HCB, PCB, PCDD/-F and PBDD/-F. Compared to the Danish national emission decentralized CHP plants are major emission sources for CH_4, NO_x, SO_2, heavy metals and HCB.

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