National Environmental Research Institute
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NERI Technical Report No. 672, 2008

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Sub-report 3 (NERI)

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Data sheet

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Abstract:	Liberalisation of the electricity market has led to Danish gas engine plants increasingly converting to the spot and regulating power markets. In order to offer regulating power, plants need to be able to start and stop the engines at the plants quickly. The liberalisation causes a considerable change of operation practice of the engines e.g. less full load operation hours /year. The project provides an inventory determining the scale of the emissions during the start and stop sequence as well as proposals for engine modifications aimed at reducing start/stop emissions. This report includes calculation of emission factors as well as an inventory of total emissions and reduction potentials.
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Contents

Preface

Liberalisation of the electricity market has led to Danish gas engine plants increasingly converting to the spot and regulating power markets. From 1 January 2005, plants > 10MW$_e$ have been operating on the whole-sale market, and from 1 January 2005 this has been extended to all plants > 5MW$_e$. Small plants joining forces can also operate on the liberalised market. Trading systems include the spot market, regulating market or the reserve market.

In order to offer regulating power, plants need to be able to start and stop the engines at the plants quickly. Previously, start/stop procedures in gas engines have been determined purely based on load considerations, which do not aim at the short start time of max. 15 minutes desirable in connection with regulating power services.

It has earlier been demonstrated that increased emissions are associated with the start and stop procedures of gas engines (Kristensen 2003). It has also been assessed that liberalisation of the electricity market and participation in systems offering regulating power will in future lead to gas engines starting and stopping more than prior to liberalisation (Decentral Kraftvarme på markedsvilkår 2004). Therefore, in the future, higher emission factors for gas engines are expected, and this project sheds light on the scale entailed. The project covers the emissions of CO, NO_X and UHC ($NMVOC+CH_4$).

Leading Danish gas engine suppliers have participated in the project, which has included considerations on engine modifications aimed at shorter start times and lower emissions in connection with start/stop procedures.

The project is reported in a main report and a range of sub-reports which all will be made available on the websites of Danish Gas Technology Centre's (DGC) and National Environmental Research Institute, University of Aarhus (NERI), (www.dgc.dk and www.dmu.dk). The current sub-report comprises:

- Preparation of revised full-load emission factors for gas engines
- Preparation of new Danish emission factors for natural gas-powered engines where start/stop emissions are take into account
- Calculation of total Danish emissions for gas engines including emissions under start/stop
- Calculation of reduction potentials for emissions through improved engine regulation under start/stop procedures

Furthermore, the independent research note *Use of environmental economic valuation to estimate damage costs for air emissions in technology assessments* (Birr-Pedersen 2007) is attached as Annex 2.

NERI prepares the Danish emissions inventories annually for the Climate Convention and for the Convention on Long-Range Transboundary

Air Pollution (LRTAP Convention). Gas engine emission factors are used in this work.

Project participants:

- Dansk Gasteknisk Center (Danish Gas Technology Centre) (DGC)
- Pon Power[1]
- Wärtsilä
- Rolls Royce
- GE Jenbacher
- National Environmental Research Institute, University of Aarhus (NERI)

In addition to the Danish engine suppliers, their respective engine manufacturers have contributed in relation to engine development.

The project has been implemented for Energinet.dk and has partially been financed by Energinet.dk's PSO funds.

[1] Withdrew during implementation of the project

Sammendrag

Liberalisering af elmarkedet har ført til at danske gasmotoranlæg i stigende grad handler på spot- og regulerkraftmarkedet. Fra 1/1 2005 har værker > 10MW_e været markedsafregnede og fra 1/1 2007 gælder det alle værker > 5MW_e. Mindre værker har også ved at gå sammen mulighed for at blive markedsafregnede. Markedsafregningen kan ske iht. spotmarkedet, regulerkraftmarkedet eller reservekraftmarkedet.

For at yde regulerkraft skal værkerne være i stand til hurtigt at starte og stoppe motorerne. Hidtil har gasmotorernes start-/stopprocedurer været fastlagt ud fra rent belastningsmæssige hensyn der ikke sigtede mod den korte starttid på højest 15 minutter, som ønskes i forbindelse med regulerkraftydelser.

Projektet omfatter dels en opgørelse over omfanget af emissionerne under start-/stopforløb og dels motorudvikling med det mål at reducere emissionerne under start/stop. Denne delrapport omfatter udarbejdelse af emissionsfaktorer og opgørelse af samlede emissioner og reduktionspotentiale.

De reviderede emissionsfaktorer for danske gasmotorer, hvori emissioner under start- og stopforløb er indarbejdet, er CO 115 g/GJ, NO_X 148 g/GJ, UHC 434 g (C)/GJ, CH_4 465 g/GJ og NMVOC 105 g/GJ. Korrektionsfaktorerne der indregner emissioner under start/stopforløb er fastlagt til 1,05 for CO, 1,00 for NO_X og 1,03 for UHC.

De beregnede emissionsfaktorer er lavere end de hidtil anvendte emissionsfaktorer der alene var baseret på fuldlastdrift. Det skyldes at der er foretaget en delvis opdatering af fuldlast emissionsfaktorerne, som er faldet de senere år. Reviderede fuldlast emissionsfaktorer er estimeret for de forskellige motortyper baseret dels på nye emissionsgrænseværdier og dels på målerapporter fra en lang række motorer.

Det samlede emissionsbidrag fra danske naturgasdrevne motorer er for 2005 beregnet til: 3642 ton CO, 4694 ton NO_X og 13792 ton (C) UHC (heraf 14787 ton CH_4 og 3327 ton NMVOC). Dermed udgør CH_4 emissionen fra motorerne 65 % af den samlede emission fra stationære forbrændingsanlæg, mens andelen for NMVOC er 14 % og NO_X andelen er 7 %.

Rolls Royce og Wärtsilä har foretaget forsøg med ændret motorstyring under start/stop med det mål at reducere emissionsbidraget herfra. For begge fabrikater er emissionsbidraget under start/stop reduceret for CO og UHC mens NO_X emissionsbidraget er steget ganske lidt (Jensen 2006).

Ved fuld implementering af den ændrede motorstyring på Rolls Royce og Wärtsilä 34 vil gasmotorernes årlige emission af CO falde med 1 %, UHC med 2 % mens NO_X vil stige med 0,5 %. Hvis det antages at start/stop korrektionsfaktorerne for alle motortyper reduceres så de højest er det samme som for de revidere Rolls Royce eller Wärtsilä 34 motorer vil den danske gasmotoremission af CO kunne reduceres med 4 %, UHC med 2 % mens NO_X vil være praktisk taget uændret. Rolls Royce og Wärtsilä har dog begge oplyst at motorændringerne ikke vil blive implementeret da motorerne allerede nu kan honorere de starttider som kræves for at yde regulerkraft og da der ikke er miljømæssige krav som gør en implementering nødvendig.

Den væsentligste miljømæssige ændring ved omlægning til markedstilpassede afregningsformer er ikke ændring i gasmotorernes emissionsfaktorer idet driftstimetallet pr motorstart har vist sig ganske konstant. Derimod vil en variation i det årlige driftstimetal som følge af prisudviklingen for el og gas slå igennem således, at der fremover kan forventes større udsving i gasmotorernes emissionsbidrag fra år til år. Ved et højprisscenarium forventes ikke større afvigelse i driftstimetal og emissionsbidrag i forhold til hvad der har været gældende hidtil. Ved et lavprisscenarium kan driftstimetallet og dermed årligt emissionsbidrag forventes at falde væsentligt.

Summary

Liberalisation of the electricity market has led to Danish gas engine plants increasingly converting to the spot and regulating power markets. From 1 January 2005, plants > $10MW_e$ have been operating in the wholesale market, and from 1 January 2005 this has been extended to all plants > $5MW_e$. Small plants joining forces can also join the liberalised market. Trading systems can include the spot market, regulating market or the reserve market.

In order to offer regulating power, plants need to be able to start and stop the engines at the plants quickly. Previously, start/stop procedures in gas engines have been determined based purely on load considerations, which do not aim at the short start time of max. 15 minutes desirable in connection with regulating power services.

The project provides an inventory determining the scale of the start/stop emissions as well as engine considerations on modifications aimed at reducing start/stop emissions. This report includes calculations of emission factors as well as an inventory of total emissions and reduction potentials.

The revised emission factors for Danish gas engines in which start/stop emissions are taken into account are: CO 115 g/GJ, NO_X 148 g/GJ, UHC 434 g (C)/GJ, CH_4 465 g/GJ and NMVOC 105 g/GJ. The correction factors which incorporate the start/stop emissions are set at 1.05 for CO, 1.00 for NO_X and 1.03 for UHC.

The revised emission factors are lower than the emission factors used to date, which were based solely on full-load operation. This is the result of a partial updating of the full-load emission factors, which have decreased in recent years. Revised full-load emission factors are estimated for the various engine types based partly on new emission limit values as well as on measurements from a wide range of engines.

The total emission contribution from Danish natural gas-powered engines for 2005 is calculated to 3,642 tonne CO, 4,694 tonne NO_X and 13,792 tonne (C) UHC (of which 14,787 tonne CH_4 and 3,327 tonne NMVOC). As a result, the CH_4 emission from engines constitutes 65% of the total emission from stationary combustion plants, whereas the share for NMVOC is 14% and the NO_X share is 7%.

Rolls Royce and Wärtsilä have carried out experiments to modify engine regulation under start/stop procedures with the aim of reducing the associated emission contribution. For both engine makers, it has been possible to reduce the emission contribution under start/stop for CO and UHC, while the NO_X emission contribution has risen slightly (Jensen 2006).

Under full implementation of the engine modifications for the Rolls Royce and Wärtsilä 34 engines, the annual emission of CO would fall by 1%, UHC by 2%, while NO_X would rise by 0.5%. If it is assumed that the

start/stop correction factors for all engine types are reduced to a maximum level equal to the modified Rolls Royce or Wärtsilä 34 engines, the Danish gas engine emission of CO could be reduced by 4 %, and UHC by 2%, while the NO_X emission would remain practically unchanged. Rolls Royce and Wärtsilä have, however, both communicated that the engine modifications will not be implemented as the existing engines already comply with the start times required to offer regulating power, and as environmental requirements do not imply a need for implementation.

The most important environmental change in converting to liberalised pricing systems is not the change in the emission factors associated with the gas engines, as the number of hours of operation per engine start has proved to be rather constant. Variability in the annual number of hours of operation resulting from price fluctuations for electricity and gas will evolve, probably resulting in greater annual variations in gas engine contributions to emissions in the future. Under a high-price scenario, large deviations from the situation experienced to date are not expected in relation to the number of hours of operation and emission contribution. Under a low-price scenario, however, the number of hours of operation and, in turn, the annual emission contribution can be expected to fall considerably.

1 Gas engines in Denmark – capacity and distribution

Based on the database for gas engines in operation in Denmark in 2005, an overview of the consumption of natural gas according to the various manufacturers and engine types has been prepared.

Figure 1 shows the consumption of natural gas according to engine make. Four engine makes dominate in Denmark: Rolls Royce (formerly Ulstein Bergen), Caterpillar, Jenbacher and Wärtsilä. The consumption of natural gas by these four comprises 89% of the total consumption of gas in gas engines in 2005.

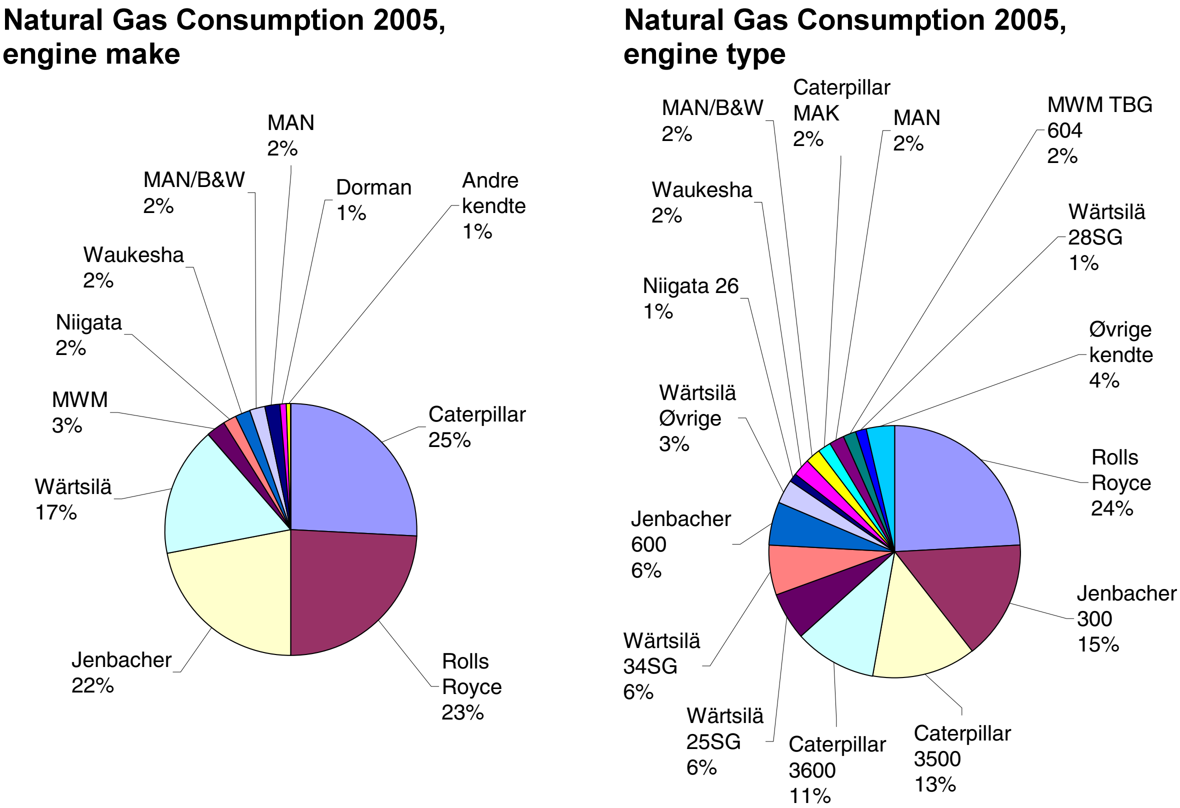

Figure 1 Consumption of natural gas 2005 according to engine make (left) and engine type (right)

Almost all engines are fitted with oxidation catalytic converters installation of which has been necessary to comply with the CO limit in the Danish regulation (Bekendtgørelse 621, 2005).

The emission measurement programme is arranged in such a way that measurements are representative for the engines which are in operation in Denmark. A detailed description of the measurement programme is found in Annex 4.

In 2007, approximately 50% of installed gas engine capacity is over the $5MW_e$ limit which means this is priced according to the market. The plants on the liberalised market either operate on the spot market or deliver system services as regulating power or reserve power.

2 Revised full-load emission factors

2.1 Background to the data

The emission factors that NERI has used until now have been based on emission measurements at full-load operation (Nielsen & Illerup 2003). These full-load emission factors are no longer representative as new lower limit values for emissions for existing engines came into effect in October 2006 (Bekendtgørelse 621, 2005). It has therefore been necessary to update the full-load factors. Only a partial updating has been carried out as a measurement programme for full-load operation was outside the scope of the project.

The update in relation to full-load emission factor is based on:

- Danish Energy Authority's Electricity and Heat Production Survey for 2005 (Energistyrelsen, 2006)
- Database containing gas engine type for all Danish gas engines (Kristensen 2003)
- The full-load emission factors used to date for the various engine types (Nielsen & Illerup 2003)
- New emission limit values (Bekendtgørelse 621, 2005)
- New full-load emission factors for Rolls Royce and Wärtsilä based on emission measurement reports made available to the project

The aggregate Danish full-load emission factors are based on emission factors from a range of different engine types as well as their associated fuel consumptions in 2005:

$$EMF_{DK\_full\_load} = \frac{\sum_{i=1}^{n} EMF_i \cdot Q_i}{\sum_{i=1}^{n} Q_i}$$

where

$EMF_{DK\_full\_load}$ *is the aggregate Danish full-load emission factor for gas engines*

EMF_i *is the full-load emission factor for engine type (group) i*

Q_i *is the fuel consumption (natural gas) in 2005 according to the Electricity and Heat Production Survey for engine type (group) i*

n *is the number of engine types (groups) from which emission factors are available*

The Danish Energy Authority's Electricity and Heat Production Survey for 2005 (Energistyrelsen, 2006) contains data for gas consumption, electricity production, etc for each individual gas engine in Denmark. The Danish Energy Authority has made the database available for the project.

In connection with a project in which emissions from decentralised CHP were mapped (Kristensen 2003), a database was compiled, coupling the energy producer census data to engine type. This dataset, after being subject to an update, has been used for this project. The dataset contains engine make, engine type and engine group. Engine groups are engine types which, as far as emissions go, can be grouped as one. For example, engines whose construction is the same apart from number of pistons are categorised in the same engine group.

Full-load emission factors for the individual engine types are, as a point of departure, set at the values that have been used to date (Nielsen & Illerup 2003). For each individual engine type, the emission factors are then compared with the new emission limit values outlined in Bekendtgørelse 621. The emission factors that lie above the new limit values are reduced to coincide exactly with the emission limit values. No consideration is given to that e.g. the UHC emission can be conceived to be rising (up to the limit value) due to engines being regulated in a different way to comply with the NO_X emission limit.

$$EMF_{i\_pol} = Min(EMF_{i\_pol\_2003}, EMF_{i\_pol\_legislatin})$$

where

EMF_{i_pol}	*is the new full-load emission factor for engine type i and the substance pol (CO, NO_X or UHC)*
$EMF_{i\_pol\_2003}$	*is the full-load emission factor for engine type i and substance pol as established in 2003 (Nielsen & Illerup 2003)*
$EMF_{i\_pol\_legislation}$	*is the emission limit value according to Bekendtgørelse 621 for engine type i and substance pol*[2]

Wärtsilä and Rolls Royce have, with permission from the plant owners, made available a large number of accredited measurement reports to update the full-load emission factors. The measurements which are included in the update have all been taken after the engines have been modified with the goal of complying with Bekendtgørelse 621. The measurements were taken in 2004-2006. The measurement data have been aggregated according to fuel consumption in 2005 (Energistyrelsen, 2006) for the individual engines. A large number of the measurements were taken immediately after the upgrading to new engine versions, i.e. just after regulation of the engines. This is not necessarily fully representative for the general operational situation, but judging by experience the emission level is however rather stable (Kristensen, 2003). The revised full-load emission factors for Wärtsilä 25SG, Wärtsilä 34SG, Rolls Royce and Rolls Royce B35:40 have been calculated as follows:

[2] The emission factor for UHC depends on the electrical efficiency and therefore is not the same for all engine types

$$EMF_{i\_full\_load} = \frac{\sum_{e=1}^{m} EMF_e \cdot Q_e}{\sum_{e=1}^{m} Q_e}$$

where

$EMF_{i\_full\_load}$ *is the full-load emission factor for engine type (group) i*

EMF_e *is the emission factor for a single engine e (average where there are several measurements available for engine e)*

Q_e *is fuel consumption according to the 'Energiproducenttællingen' 2005 for engine e*

m *is the number of engines in group i from which measurements are available*

For Wärtsilä, the measurements available to NERI cover 82% of total consumption in the engine group 25SG and 61% of total consumption in the engine group 34SG. For Rolls Royce the measurements NERI have available cover 65% of consumption by Rolls Royce engines in 2005. Furthermore, emission factors have been calculated for the new Rolls Royce type B35:40. Only two engines of this type were in operation in 2005, but more have come since. A detailed account of the number of measurements, distribution, etc. for the accredited measurement data collected can be found in Annex 4.

2.2 Individual engine types

Table 1 shows the former and the new full-load emission factors for the individual engine types (groups). It is apparent that the full-load emissions in several engine types have fallen considerably in recent years. The revised full-load factors form the basis for the further calculation.

Table 1 Full-load emission factors[6)] and electrical efficiency for the engine types, groups [former emission factors]

Engine type (group)	Natural gas consumption 2005 [TJ]	Electrical efficiency [%]	CO [g/GJ]	NO_X [g/GJ]	UHC (C) [g/GJ]
Rolls Royce[4)5)]	7686	[39,4] 41,7	[225] 68	[232] 156	[648] 483
Jenbacher 300	4881	[nr[1]] 38,4	[129] 129	[169] 169	[235] 235
Caterpillar 3500	4256	[nr[1]] 36,3	[110] 110	[137] 137	[434] 434
Caterpillar 3600	3364	[nr[1]] 39,2	[145] 145	[91] 91	[611] 611
Wärtsilä 25SG[4)]	1877	[37,2] 39,9	[248] 65	[157] 127	[479] 475
Wärtsilä 34SG[4)]	2032	[41,2] 41,5	[163] 108	[121] 137	[413] 402
Jenbacher 600	1777	[nr[1]] 38,8	[222] 156	[169] 169	[516] 516
Wärtsilä Other	957	[nr[1]] 40.2	[135] 135	[200] 172	[92] 92
Niigata 26	419	[nr[1]] 38.0	[122] 122	[93] 93	[891] 593
Waukesha	656	[nr[1]] 33.3	[216] 156	[74] 74	[608] 519
MAN/B&W	593	[nr[1]] 38.0	[80] 80	[142] 142	[781] 593
Caterpillar MAK	593	[nr[1]] 43.4	[41] 41	[134] 134	[466] 466
MAN	590	[nr[1]] 33.1	[165] 156	[125] 125	[74] 74
MWM TBG 604	524	[nr[1]] 35.1	[177] 156	[169] 169	[161] 161
Wärtsilä 28SG	435	[nr[1]] 41.1	[265] 156	[130] 130	[473] 473
MWM TBG 620	285	[nr[1]] 38.1	[213] 156	[239] 172	[164] 164
DORMAN	282	[nr[1]] 34.6	[294] 156	[108] 108	[194] 194
FRICHS mini[2)]	62	[nr[1]] 29.8	[256] 256	[2802] 2802	[87] 87
Other	534	-	-	-	-
Rolls Royce B35:40-V12 AG[3)4)]	Not calculated	44,6	19	158	303

1. nr: no recalculation
2. Smaller engine that is not included in Bekendtgørelse 621
3. New Rolls Royce engine, data not included in the subsequent calculations
4. Based on emission measurements made available for the project by plant owners (Wärtsilä and Rolls Royce engines)
5. Formerly Ulstein Bergen
6. Updated full-load factors based on new emission limit values in Bekendtgørelse 621 and on measurement reports for full-load operation made available by Wärtsilä and Rolls Royce

Detailed data concerning the revised emission factors for Rolls Royce and Wärtsilä are attached in Annex 4.

2.3 Aggregate full-load emission factors for Danish gas engines

The new Danish full-load emission factors for gas engines are shown in Table 2. The CO emission factor is 37% lower than previously, NO_X 12% lower and UHC 13% lower. At the same time electrical efficiency has become 0.9% higher.

Engine-specific emission factors have been available for over 98% of the consumption of natural gas in gas engines in 2005.

Table 2 Full-load emission factors

	Full-load emission factor g/GJ	Former emission factor g/GJ	Change in full-load emission factor	Full-load emission factor mg/m$^3{}_n$ (ref. 5% O_2)
CO	109	175	-37%	351
NO_X	148	168	-12%	473
UHC (C)	420	485	-13%	1347
- CH_4	450	520	-13%	1444
- NMVOC	101	117	-13%	325
	%	%		%
Electrical efficiency	39.2	38.3	+0.9%-point	39.2

Gas consumption is distributed slightly differently according to the various engine types than was the case when the earlier emission factors were prepared. This however has shown itself to be a slight shift which does not change the aggregate emission factors markedly.

The most important reason for the lower emission factors is the new emission limit values and ensuing engine modifications.

The emissions from both Rolls Royce engines and Wärtsilä engines lie considerably under the limit values. This implies that an equivalent update based on measurements for the remaining engine types could give a lower estimate for the aggregate full-load emission factors for Danish gas engines.

3 Inclusion of start/stop emissions

Revised Danish emission factors for gas engines have been calculated in which start/stop emissions are taken into consideration. In order to reveal the sensitivity of the emission factors to uncertain operational pattern data (see page 22, for further details), additional measurements of emission factors at various, assumed, standardised patterns of operation have been taken. Furthermore, emission factors with start/stop correction have been calculated for the different engine types as well as for engines with different pricing arrangements. Finally, time-series have been prepared for emission factors for use in NERI's future reporting of Danish emission totals for the Climate Convention and the Convention on Long-Range Transboundary Air Pollution.

3.1 Background to the data

The revised emission factors, which take start/stop emissions into account, are based on the following data sources:

- Census data from energy producers (Electricity and Heat Production Survey) for 2005 (Danish Energy Authority 2006)
- Revised full-load emission factors (described above)
- A database that couples engine type to the Electricity and Heat Production Survey
- DGC's emission measurements under start/stop procedures for 12 engines (Jensen & Andersen 2006).
- Dataset for operational patterns based on:
  - Electricity and Heat Production Survey 2005
  - Operation data from individual plants collected by DGC
  - A range of assumptions made by NERI

3.1.1 Start/stop emissions measurement

DGC has taken start/stop emission measurements for 12 gas engines (Jensen & Andersen 2006). Additionally, DGC produced the data for start/stop measurements collected before the work in this project begun. However, the revised emission factors are alone determined on the basis of the measurements taken during this project as they have been processed with greater level of detail than the earlier measurements.

The 12 start/stop measurements are distributed according to engine type as shown in Table 3. The distribution corresponds with the distribution of the consumption of gas among engine types. Selection of the engine types to be measured was carried out by NERI and is described in Annex 1. Plant selection was made by DGC in collaboration with the engine supplier. For each individual engine, measurements have been taken under full-load operation and under a cold start, a warm start and a stop procedure.

Table 3 Start/stop measurements distributed according to engine type

Engine make	Engine type (group)	No. of measurements
Rolls Royce	Rolls Royce	3
Caterpillar	CAT 3500	2
Caterpillar	CAT 3600	2
Jenbacher	JMS 300	2
Jenbacher	JMS 600	1
Wärtsilä	25SG	1
Wärtsilä	34SG	1

Warm starts and cold starts are treated separately. In connection with an engine starting or stopping unintentionally, a number of warm starts can occur in a row.

11 out of the 12 engines that were included in the measurement programme were fitted with oxidation catalytic converters to reduce the CO emission. For engines without CO catalysts the difference in CO emission between cold and warm starts must be expected to be lower. To comply with Bekendtgørelse 621, moreover, it has been necessary from the end of 2006 to install oxidation catalytic converters on virtually all gas engines[3].

The dataset below from DGC's sub-report (Jensen & Andersen 2006) forms the basis for NERI's further calculations.

[3] Only a few engines can comply with the CO limit values without a catalytic converter. The number is so small that in the calculations it presents no problem to ignore the fact that some engines without catalytic converters are in operation. NERI estimates on the basis of information from DGC (Andersen 2007) that engines without catalytic converters constitute less than 1% of natural gas consumption.

Table 4 Emission measurements under start/stop procedures (Jensen & Andersen 2006) & (Jensen 2006)

Engine		CO [g/MJ]	NO_X [g/MJ]	UHC [g/MJ]	Energy [MJ]
#1 Wärtsilä 25	Cold start	0.143	0.111	0.653	4 175
	Warm start	0.077	0.113	0.645	4 532
	Stop	0.085	0.111	1.312	2 663
	Full-load (1 hour)	0.062	0.139	0.340	27 315
#2 Wärtsilä 34	Cold start	0.041	0.084	0.345	15 522
	Warm start	0.046	0.116	0.485	9 589
	Stop	0.056	0.054	0.524	4 054
	Full-load (1 hour)	0.029	0.110	0.257	48 829
#3 Rolls Royce	Cold start	0.102	0.112	0.793	5 468
	Warm start	0.096	0.031	2.642	1 440
	Stop	0.075	0.117	0.946	4 786
	Full-load (1 hour)	0.053	0.225	0.435	23 188
#4 Rolls Royce	Cold start	0.330	0.113	0.750	4 721
	Warm start	0.407	0.075	0.842	5 203
	Stop	0.411	0.094	0.814	4 430
	Full-load (1 hour)	0.250	0.155	0.460	22 708
#5 Rolls Royce	Cold start	0.102	0.165	0.717	10 422
	Warm start	0.078	0.114	0.964	5 704
	Stop	0.102	0.053	1.604	6 094
	Full-load (1 hour)	0.081	0.132	0.496	29 490
#6 Jenbacher 600	Cold start	0.179	0.086	0.635	2 656
	Warm start	0.201	0.093	0.714	4 601
	Stop	0.366	0.162	0.695	2 225
	Full-load (1 hour)	0.129	0.058	0.466	26 855
#7 Jenbacher 300	Cold start	0.089	0.229	0.328	1 192
	Warm start	0.074	0.191	0.280	433
	Stop	0.217	0.251	0.301	375
	Full-load (1 hour)	0.097	0.212	0.292	6 925
#8 Jenbacher 300	Cold start	0.127	0.191	0.316	688
	Warm start	0.235	0.198	0.445	284
	Stop	0.071	0.213	0.308	520
	Full-load (1 hour)	0.056	0.167	0.273	8 577
#9 Caterpillar 3500	Cold start	0.070	0.232	0.524	1 446
	Warm start	0.067	0.301	0.429	1 344
	Stop	0.054	0.214	0.440	1 263
	Full-load (1 hour)	0.053	0.288	0.464	10 433
#10 Caterpillar 3500	Cold start	0.518	0.521	0.410	2 543
	Warm start	0.616	0.728	0.329	1 605
	Stop	0.043	0.175	0.462	1 763
	Full-load (1 hour)	0.012	0.096	0.388	17 897
#11 Caterpillar 3600	Cold start	0.056	0.099	1.432	2 101
	Warm start	0.059	0.114	0.964	1 273
	Stop	0.054	0.053	1.604	2 114
	Full-load (1 hour)	0.067	0.062	0.656	25 325
#12 Caterpillar 3600	Cold start	0.056	0.108	0.885	4 008
	Warm start	0.050	0.068	1.255	5 702
	Stop	0.063	0.061	0.666	5 164
	Full-load (1 hour)	0.067	0.073	0.586	34 278

3.1.2 Aggregate start/stop data for the individual engine types

For the types of engine where start/stop emission measurement is only made from a single engine, the measurement data are used directly, as shown in Table 4. For the engine types where several measurements have been made, NERI has aggregated the average values for start/stop emission factors. In this aggregation the emission factors are weighted in relation to the individual engine's consumption of natural gas under, respectively, a warm start and a cold start, a stop period or one hour's operation. The aggregation is undertaken as follows:

$$EMF_{pol,a} = \frac{\sum_{i=1}^{n} EMF_{pol,i} \cdot Q_i}{\sum_{i=1}^{n} Q_i}$$

where:

Q_i	*is the natural gas consumption for engine i of type a*
n	*is the number of engines of type a where start/stop measurements have been made*
$EMF_{pol,I}$	*is the emission factor for the substance pol, for engine i of type a*
$EMF_{pol,a}$	*is the emission factor for the substance pol, for engine type a*

The calculations are made for each of the 4 operational states: a warm start, a cold start, a stop and an hour's full-load operation.

The aggregate start/stop emission factors for the engine types are shown in Table 5. For use in the distribution of annual consumption of natural gas according to warm start, cold start, stop and full-load, the natural gas consumptions for each of these operative states are summed for each engine type. These consumptions are subsequently used solely to distribute the annual consumption of the individual engine between cold start, warm start, stop and full-load conditions[4]. The consumption sums for the four operative states are also listed in Table 5.

$$Q_{l,a} = \sum_{i=1}^{n} Q_{l,i}$$

where:

$Q_{l,a}$	*is the natural gas consumption for a under operational situation l (warm start, cold start, stop or 1 hour's full-load operation)*
$Q_{l,i}$	*is the natural gas consumption for engine i of type a under operative state l (warm start, cold start, stop or 1-hour full-load operation)*
n	*is the number of engines of type a where a start/stop measurement has been taken*

For engine types (groups) that are not included in the start/stop measurement programme, energy-weighted[5] averages for the seven engine groups that were included are used. Engine groups that were not cov-

[4] Natural gas consumptions are summed in order to be able to calculate e.g. How large is consumption of natural gas under a warm start for engine type a compared with consumption under 1-hour's full-load operation?
[5] Energy weighted according to the Electricity and Heat Production Survey for 2005 (Danish Energy Authority 2006)

ered by the start/stop measurement programme constitute 19% of natural gas consumption in 2005.

Table 5 Input data for inclusion of start/stop emissions

	Engine type	Wärtsilä 25	Wärtsilä 34	Rolls Royce	Jenbacher 600	Jenbacher 300	Caterpillar 3500	Caterpillar 3600	Other
Full-load operation 1 hour	Energy MJ[1)]	27315	48829	75387	26855	15502	28330	59603	45391
	CO g/MJ	0.062	0.029	0.088	0.129	0.074	0.027	0.067	0.069
	NO_X g/MJ	0.139	0.110	0.149	0.058	0.187	0.167	0.068	0.139
	UHC g/MJ	0.340	0.257	0.349	0.466	0.281	0.416	0.616	0.382
1 cold start	Energy MJ[1)]	4175	15522	20611	2656	1879	3990	6110	9633
	CO g/MJ	0.143	0.041	0.154	0.179	0.151	0.356	0.056	0.166
	NO_X g/MJ	0.111	0.084	0.139	0.086	0.130	0.416	0.105	0.169
	UHC g/MJ	0.653	0.345	0.744	0.635	0.540	0.451	1.073	0.655
1 warm start	Energy MJ[1)]	4532	9589	12346	4601	717	2948	6975	6593
	CO g/MJ	0.077	0.046	0.219	0.201	0.190	0.366	0.052	0.191
	NO_X g/MJ	0.113	0.116	0.088	0.093	0.101	0.534	0.077	0.167
	UHC g/MJ	0.645	0.485	1.108	0.714	0.676	0.374	1.202	0.809
Stop	Energy MJ[1)]	2663	4054	15310	2225	895	3026	7278	6825
	CO g/MJ	0.085	0.056	0.183	0.366	0.345	0.047	0.060	0.171
	NO_X g/MJ	0.111	0.054	0.085	0.162	0.175	0.191	0.059	0.121
	UHC g/MJ	1.312	0.524	1.170	0.695	0.638	0.453	0.939	0.849

The dataset is used to distribute the annual natural gas consumption between full load, cold start, warm start and stop.

The aggregate emission factors for the engine types are shown in Chapter 3.2.2.

3.1.3 Operational patterns

In order to be able to quantify the scale of start/stop emissions, it is important to know the annual number of hours of operation, the number of starts/stops per year and the distribution between cold starts and warm starts.

Number of hours of operation

The number of hours of operation is not included directly in the Electricity and Heat Production Survey but as both installed electrical capacity and annual electricity production are included, the number of hours of operation can be estimated on the basis of these. The engines in 2005 were in operation 10 hours per day on average (energy weighted average is 11 hours). In further calculation, it is the number of hours of operation for the individual engines that is used.

Number of starts/stops

A complete dataset for the number of starts per year has not been available. DGC has collected data from 10 of the 12 engines which came under the emission measurement programme and has supplemented these with data from a further 20 plants (Jensen, 2006). The dataset included the information below, which however, is not complete for all engines:

- Number of annual hours of operation under the former pricing arrangement (three-part tariff)
- Number of annual hours of operation under the current pricing arrangement (three-part tariff /spot market /regulating market)
- Number of annual starts under the former pricing arrangement (three-part tariff)
- Number of annual starts under the current pricing arrangement (three-part tariff /spot market / regulating market)

And plant-specific data:

- Engine type (group)

The engine types that DGC has chosen to select data from constitute a representative sample of Danish engines described in DGC's note (Andersen 2007). Data has been collected in 2006/2007 and therefore comprises a more recent dataset than the data the calculations are otherwise based on. In Table 6 aggregate data is shown for the various patterns of operation.

Table 6 Operation data based on DGC's data collection from 30 engines (Jensen, 2006)

	Number of engines	No. of hours of operation [h]			Starts [-]			No. of hours of operation per start [h]		No. of hours compared with earlier[1)]	No. of starts compared with earlier[1)]
		Average		St.dev.	Average		St.dev.	Average	St.dev.		
		Year	Day		Year	Day					
Three-part tariff	13	3792	10.4	786	379	1.0	111	10.5	1.7	94%	96%
Spot market	12	2633	7.2	942	243	0.7	80	10.8	2.0	65%	83%
Regulating market	5	500	1.4	300	56	0.2	17	9.6	4.9	14%	22%

[1)] Compared with earlier operation on the three-part tariff

The number of hours of operation and number of starts are markedly lower for engines on the regulating power market than for those on the three-part tariff. Engines on the spot market also have fewer hours of operation and fewer starts than engines on the three-part tariff.

It is apparent that there is no significant difference between the number of hours of operation per engine start for engines with pricing arrangements according to the three-part tariff and spot market, respectively. Hours of operation per start are slightly lower for engines operating with regulating power, but the difference is not as large as expected. This means that the start/stop emission does not have a significantly higher weight for engines on regulating power than engines on the three-part tariff/spot market.

On the basis of the 30 datasets, NERI has made a range of assumptions which are used in the complete Electricity and Heat Production Survey dataset.

- Engines with less than 900 annual[6] hours of operation are assumed to have the same number of hours of operation per start as engines on

[6] Equivalent to 2.5 hours of operation per day

the regular market. A small number of engines on the reserve market are therefore included in this category.

- Engines with between 900 and 3,200 annual[7] hours of operation are assumed to have the same number of hours of operation per start as engines on the spot market.
- Engines with over 3,200 annual hours of operation are assumed to have the same number of hours of operation per start as engines on the three-part tariff.

Table 7 shows, based on the above assumptions, average number of hours of operation and number of starts for the three pricing groups. The further calculations however are based on plant-specific data. It must be assumed that more engines operate on the spot market or the regulating market now than in the 2005 dataset used.

Table 7 Aggregate data for pattern of operation (based on 2005 data[1)])

	Number of engines in EPT 2005	Operation time [h]		Annual no. of starts [-]	
		Average	St.dev.	Average	St.dev.
Three-part tariff	361	4456	1071	424	102
Spot market	168	2410	642	223	59
Regulating market	17	493	296	51	31
All engines	546	3703	1449	351	139

[1)] Distribution according to trading arrangements based on NERI's assumptions

Distribution between cold starts and warm starts

The distribution between cold starts and warm starts has not been known at the plants that DGC have collected data for.

In reporting the project *Decentral kraftvarme på markedsvilkår* (2004) it is stated that there are typically 40-60 unintentional stops per year. These data stem from 10 plants and include both gas turbines and engines. The dataset was collected when the plants were still operating according to the three-part tariff.

Based on the above, NERI has assumed that 12% of the starts are warm starts, while the remaining 88% are cold starts.

Additional calculations

Data concerning the number of starts/stops and the distribution between warm starts and cold starts is rather uncertain. Therefore additional calculations based on different standardised patterns of operation are included to shed light on the sensitivity of the operation input data.

The first group of calculation examples includes assumption of differing numbers of annual starts for all engines. Number of hours of operation and the distribution between warm and cold starts are assumed as described above.

Another group of examples stems from DGC's sub-report 1. These calculations are based on 16 hours' full-load operation per 24-hour period and respectively 1, 2 or 4 daily warm or cold starts.

[7] Equivalent to 2.5-8.8 hours of operation per day

3.2 Aggregate emission factors including start/stop

3.2.1 Aggregrate emission factors for Danish gas engines, method

Aggregate Danish emission factors are calculated on the basis of engine-specific data for fuel consumption and estimated emission factors for each individual engine.

The aggregate Danish emission factors are thereafter calculated as follows:

$$EMF_{pol,DK} = \frac{\sum_{i=1}^{n} Q_i \cdot EMF_{pol,i}}{\sum_{i=1}^{n} Q_i}$$

hvor

$EMF_{pol,DK}$ is the Danish gas engine emission factor for substance pol, start/stop corrected

Q_i is fuel consumption for engine i

$EMF_{pol,i}$ is the start/stop corrected emission factor for motor i and substance pol

n is the number of gas engines in Denmark (according to the Electricity and Heat Production Survey for 2005)

<u>Fuel consumption</u> for each individual gas engine refers to the Electricity and Heat Production Survey 2005 and is distributed between full-load operation, cold start, warm start and stop.

Fuel consumption:

$$Q_{full,n} = z_{n,m} \cdot h_n \cdot Q_{full,m}$$

$$Q_{w,n} = z_{n,m} \cdot w_n \cdot Q_{w,m}$$

$$Q_{c,n} = z_{n,m} \cdot c_n \cdot Q_{c,m}$$

$$Q_{s,n} = z_{n,m} \cdot s_n \cdot Q_{s,m}$$

where

$Q_{full,n}$ is annual fuel consumption at full-load for engine n

$Q_{w,n}$ is annual fuel consumption under warm starts for engine n

$Q_{c,n}$ is annual fuel consumption g under cold starts for engine n

$Q_{s,n}$ is annual fuel consumption under a stop procedure for engine n

$z_{n,m}$ *is a scaling factor for fuel consumption for engine n of type m.*

h_n *is annual number of hours of operation*

$Q_{full,m}$ *is fuel consumption for one-hour's full-load operation of engine type m (see Table 5)*

w_n *is annual number of warm starts*

$Q_{w,m}$ *is fuel consumption under a warm start for an engine of type m (see Table 5)*

c_n *is annual number of cold starts*

$Q_{c,m}$ *is fuel consumption under a cold start for an engine of type m (see Table 5)*

s_n *is number of annual stops*

$Q_{s,m}$ *is fuel consumption under a stop procedure for an engine of type m (see Table 5)*

The scaling factor $z_{n,m}$ is an expression of the fact that engines with different effect are included within the same engine group. The scaling factor is calculated as:

$$z_{n,m} = \frac{h_n \cdot Q_{full,m} + w_n \cdot Q_{w,m} + c_n \cdot Q_{c,m} + s_n \cdot Q_{s,m}}{Q_n}$$

where

$z_{n,m}$ *is the scaling factor for fuel consumption for engine n of type m*

h_n *is annual hours of operation*

$Q_{full,m}$ *is fuel consumption for an hour's operation of engine type m (see Table 5)*

w_n *is annual number of warm starts*

$Q_{w,m}$ *is fuel consumption under a warm start for an engine of type m (see Table 5)*

c_n *is annual number of cold starts*

$Q_{c,m}$ *is fuel consumption under a cold start for an engine of type m (see Table 5)*

s_n *is annual number of stops*

$Q_{s,m}$ *is fuel consumption under a stop procedure for an engine of type m (see Table 5)*

Q_n *is the annual fuel consumption for engine n according to the Electricity and Heat Production Survey 2005*

Overall, the distribution of fuel consumption is: 97% under full-load operation, 1.5% under cold starts, 0.1% under warm starts and 1.2% under stop procedures.

For each individual engine individual emission factors are calculated based on the distribution of fuel consumption between full-load operation, warm start, cold start and stop procedures.

$$EMF_{pol,n,m} = EMF_{pol,m} \cdot k_{pol,n,m}$$

where:

$EMF_{pol,n,m}$ *is the start/stop corrected emission factor for substance pol for engine n of type m*

$EMF_{pol,m}$ *is the full-load emission factor for engine type m (revised full-load emission factors, see Table 1)*

$k_{pol,n,m}$ *is the correction factor substance pol for engine n of type m*

The correction factor for inclusion of start/stop emission a is calculated as follows:

$$k_{pol,n,m} = \frac{Q_{full,n} \cdot EMF_{full,m} + Q_{w,n} \cdot EMF_{w,m} + Q_{c,n} \cdot EMF_{c,m} + Q_{s,n} \cdot EMF_{s,m}}{Q_n \cdot EMF_{full,m}}$$

where:

$k_{pol,n,m}$ *is the correction factor correction factor for substance pol for engine n of type m*

$Q_{full,n}$ *is annual fuel consumption at full-load for engine n*

$Q_{w,n}$ *is annual fuel consumption under warm starts for engine n*

$Q_{c,n}$ *is annual fuel consumption under cold starts for engine n*

$Q_{s,n}$ *is annual fuel consumption under stop procedures for engine n*

Q_n *is annual fuel consumption for engine n*

$EMF_{full,m}$ *is the emission factor at full-load for motor m (see start/stop measurements, Table 5)*

$EMF_{w,m}$ *is the emission factor under warm starts for engine m*

$EMF_{c,m}$ *is the emission factor under cold starts for engine m*

$EMF_{s,m}$ *is the emission factor under stop procedures for engine m*

Note that the correction factor is calculated on the basis of measurement results from start/stop measurements, while the aggregate emission factor is calculated on the basis of the revised full-load emission factors.

3.2.2 Aggregate emission factors for Danish gas engines, results

The revised CO emission factor is 35% lower than the factor used previously (Nielsen & Illerup 2003), the NO_x emission factor is 12% lower and UHC 11% lower. That the emission factors are lower is a result of the revised full-load emission factors being significantly lower than the previous ones. Inclusion of start/stop emissions gives, in relation to the full-load emission factors, a CO emission factor that is 5% higher and a UHC emission factor that is 3% higher. The NO_X emission factor is largely the same with inclusion of start/stop emissions.

Table 8 Danish gas engine emission factors incl. start/stop emission

	New emission factors (and change compared with the previous emission factor)	Aggregate correction factor	New full-load emission factor
CO [g/GJ]	115 (-35%)	1.05	109
NO_X [g/GJ]	148 (-12%)	1.00	148
UHC [g(C)/GJ]	434 (-11%)	1.03	420
- of which CH_4 [g/GJ]	465 (-11%)	1.03	450
- of which NMVOC [g/GJ]	105 (-11%)	1.03	101

3.2.3 Emission factors for the individual engine types

Emission factors and correction factors for each of the engine types are shown in Table 9. Fields marked grey are not engine type specific. The calculations are made according to the same method as the calculations for the aggregate total Danish emission factors and start/stop correction factors, just for each engine type individually.

The pattern of operation in 2005 for the individual engines is part of the input data for calculation of start/stop correction factors. If an engine type in 2005 has only been in operation for few hours and with many starts, the correction factor arrived at is relatively high, even if this cannot be explained purely in terms of engine construction or control.

FRICHS mini engines lie under the effect limit boundary for Bekendtgørelse 621 and therefore are not required to comply with this. The CO and NO_X emission levels clearly lie outside the general levels. The same is true for several other very small engines found under the group 'Other'.

CO emission factors for the various engine types lie between 20-163 g/GJ[8], the NO_X emission factors are in the range 74-172 g/GJ[8] and the UHC factors in the range 76-619 g/GJ[8], though with an interval 239-619 g/GJ for the predominant engine types.

NO_X correction factors for start/stop emissions lie close to 1.00 for all engine types. For CO and UHC all the correction factors are over 1.00 and large disparity is evident between engine types.

For Caterpillar 3500 the correction factor for CO is noticeably high. This is due to abnormal operational conditions and it does not necessarily follow that this engine will have such a high correction factor under normal

[8] As FRICHS mini engines can be disregarded here

operation. The dataset is included in the aggregation, however, as such conditions of operation will occur from time to time.

Table 9 Emission factors (incl. start/stop emissions) and start/stop correction factors for the engine types (groups)

Engine type (group)	Natural gas consumption 2005 [TJ]	Electrical efficiency [%]	CO [g/GJ]			NO_X [g/GJ]			UHC (C) [g/GJ]		
			Full-load	Correction factor	Emission factor	Full-load	Correction factor	Emission factor	Full-load	Correction factor	Emission factor
Rolls Royce	7686	41.7	68	1.04	70	156	0.99	154	483	1.07	518
Jenbacher 300	4881	38.4	129	1.03	133	169	1.00	169	235	1.02	239
Caterpillar 3500	4256	36.3	110	1.16	128	137	1.02	140	434	1.00	435
Caterpillar 3600	3364	39.2	145	1.00	144	91	1.00	91	611	1.01	619
Wärtsilä 25SG	1877	39.9	65	1.02	66	127	1.00	127	475	1.04	494
Wärtsilä 34SG	2032	41.5	108	1.02	110	137	0.99	136	402	1.02	409
Jenbacher 600	1777	38.8	156	1.02	159	169	1.02	172	516	1.01	520
Wärtsilä Other	957	40.2	135	1.05	141	172	1.00	172	92	1.03	95
Niigata 26	419	38.0	122	1.05	127	93	1.00	93	593	1.03	612
Waukesha	656	33.3	156	1.05	163	74	1.00	74	519	1.03	536
MAN/B&W	593	38.0	80	1.05	84	142	1.00	142	593	1.03	612
Caterpillar MAK	593	43.4	41	1.05	43	134	1.00	134	466	1.03	481
MAN	590	33.1	156	1.05	163	125	1.00	125	74	1.03	76
MWM TBG 604	524	35.1	156	1.05	163	169	1.00	169	161	1.03	167
Wärtsilä 28SG	435	41.1	156	1.05	163	130	1.00	131	473	1.03	488
MWM TBG 620	285	38.1	156	1.05	163	172	1.00	172	164	1.03	170
DORMAN	282	34.6	156	1.05	163	108	1.00	108	194	1.03	200
FRICHS mini	62	29.8	256	1.05	268	2802	1.00	2808	87	1.03	90
Other	534	39.2	109	1.05	115	148	1.00	148	420	1.03	434
Rolls Royce B35:40-V12 AG	Not calculated	44.6	19	1.05	20	158	1.00	158	303	1.03	313

3.2.4 Emission factors for engines operating under different pricing arrangements

Correction factors and emission factors for engines operating according to the three-part tariff, spot market and regulating market are shown in Table 10. The calculations have been carried out according to the same method as above, just grouped according to trading arrangements. These groupings are based on NERI assumptions (page 22).

It appears that the correction factors for CO and UHC are only slightly higher for engines on the regulating market than for engines operating according to the three-part tariff or spot market. This means that the aggregate Danish emission factors will only change marginally even if a significant proportion of the Danish gas engines convert to the regulating market in future; though, under the assumption that the pattern of operation for engines on regulating power, as found in this project, continues not to involve markedly fewer full-load hours per engine start than engines on the three-part tariff.

Table 10 Emission factors (incl. start/stop emissions) and start/stop correction factors under different trading arrangements

Engine type (group)	Natural gas consumption 2005 [TJ]	CO [g/GJ]			NO_X [g/GJ]			UHC (C) [g/GJ]		
		Full-load	Correction factor	Emission factor	Full-load	Correction factor	Emission factor	Full-load	Correction factor	Emission factor
Three-part tariff	24661	108	1.05	113	149	1.00	149	425	1.03	438
Spot market	7062	115	1.04	120	144	1.00	144	405	1.03	417
Regulating power	80	120	1.06	128	130	1.00	130	376	1.05	393

3.2.5 Time-series for emission factors

An emission factor time-series for gas engines has been prepared earlier (Nielsen & Illerup 2003). These emission factors were all based on full-load operation. In order to ensure consistency, in future, revised emission factors which contain start/stop correction[9] will be used for the entire time-series. It is assumed that the start/stop correction factors for 2005 can be used for the entire time-series. The revised emission factors are shown in Table 11.

Table 11 Time-series for emission factors [g/GJ]

Year	CO		NO_X		UHC		CH_4		NMVOC	
	Full-load	Start/stop corrected 1)	Full-load	Start/stop corrected 1)	Full-load	Start/stop corrected 1)	Full-load	Start/stop corrected 1)	Full-load	Start/stop corrected 1)
Before 1990	177	185	306	306	251	259	269	278	61	63
1990	181	189	276	276	240	248	257	266	58	60
1991	202	211	241	241	279	288	299	309	67	69
1992	203	212	235	235	324	335	347	359	78	81
1993	217	227	214	214	508	524	545	562	123	127
1994	216	226	199	199	563	581	604	623	136	140
1995	212	222	194	194	571	590	612	632	138	142
1996	211	221	193	193	556	574	596	615	134	138
1997	174	182	170	170	498	514	534	551	120	124
1998	174	182	167	167	490	506	525	542	118	122
1999	174	182	167	167	489	505	524	541	118	122
2000	175	183	168	168	485	501	520	537	117	121
2001	175	183	168	168	485	501	520	537	117	121
2002	175	183	168	168	485	501	520	537	117	121
2003	175	183	168	168	485	501	520	537	117	121
2004	153	160	161	161	463	478	497	513	112	115
2005	131	137	154	154	442	456	474	489	107	110
2006	109	115	148	148	420	434	450	465	101	105

[9] NERI will use the revised emission factors in the annual emission inventories. The amended emission factor for 1990 will however not be of significance for the assigned amount, which forms the basis for the greenhouse gas reduction requirements for 2008-12. Assigned amounts are finalised on the basis of the emission inventory prepared in 2006.

The same start/stop correction factor is assumed for all years. The correction factors are 1.05 for CO, 1.00 for NO_X and 1.03 for UHC.

The revised full-load emission factors that are determined in this project can be used from the end of 2006, the point at which the Danish regulation, Bekendtgørelse 621 came into force. The engine upgrading that occurred in connection with the regulation has taken place over a couple of years. NERI has chosen to use the new emission factors from, and including, 2006 and has prepared a linear time-series back to the year 2003. The factors are assumed unchanged in 2000-2003.

3.3 Additional calculations

3.3.1 Various assumptions regarding number of starts/stops

As mentioned above, the number of annual starts/stops is uncertain as the underlying data is uncertain. Therefore, as a supplementary measure, an uncertainty analysis has been carried out where emission factors are calculated according to various potential numbers of starts. All engines here are assumed to have the same number of starts per year. The number of hours of operation and distribution between warm and cold starts remains unchanged in relation to the calculations above. The results of the uncertainty analysis are shown in Table 12 and Figure 2.

In extreme conditions of operation – i.e. one start per week and four starts per day – the calculated CO emission factors diverge at the most 12% from the new emission factors (from Table 8). The UHC emission factor diverges max. 9% while the NO_X factor due to a correction factor of 1.00 is unaffected.

Table 12 Danish gas engine emission factors incl. start/stop emission, varying numbers of annual starts

	Starts per year[1)]	CO [g/GJ]	NO_X [g/GJ]	UHC [g(C)/GJ]
1 start per week	52	110	148	422
2 starts per week	104	111	148	424
5 starts per week	261	113	148	430
1 start per day	365	115	148	434
2 starts per day	730	120	148	447
3 starts per day	1095	124	148	460
4 starts per day	1460	128	148	471
Revised emission factors	-	115	148	434

1) Assumption of 12% warm starts, 88% cold starts

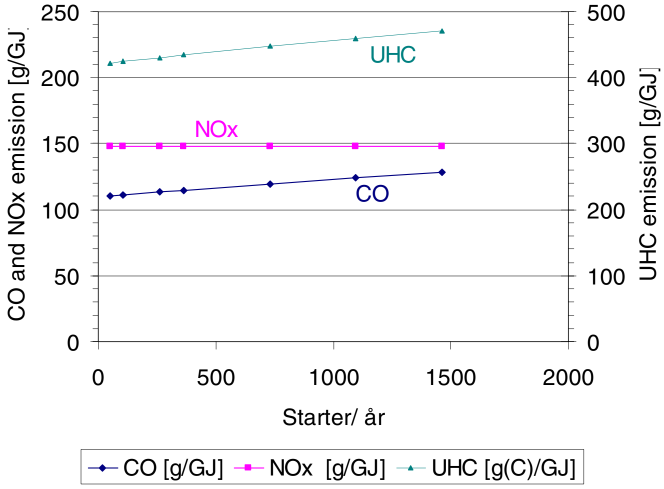

Figure 2 Danish gas engine emission factors incl. start/stop emission, with varying numbers of annual starts

3.3.2 DGC's example calculations

In DGC's sub-report 1, 6 calculation examples for different patterns of operation are used. These have been applied and the results are shown in Table 13. Here less sensitivity is evident in relation to the number of starts/stops as full-load operation time has been increased to 16 hours/day, which is considerably higher than under actual conditions of full-load operation.

Table 13 Danish gas engine emission factors incl. start/stop emission, DGC's example calculations

	Starts per year	CO [g/GJ]	NO_X [g/GJ]	UHC [g(C)/GJ]
16 hours' full-load operation, 1 cold start/day	365	114	146	428
16 hours' full-load operation, 1 warm start/day	365	114	146	429
16 hours' full-load operation, 2 cold starts/day	730	117	146	437
16 hours' full-load operation, 2 warm starts/day	730	116	146	438
16 hours' full-load operation, 4 cold starts/day	1460	123	146	453
16 hours' full-load operation, 4 warm starts/day	1460	122	146	456
Revised emission factors	-	115	148	434

4 Total emission contribution from start/stop procedures in gas engines

4.1 Emission 2005

The total emission contribution from Danish natural gas-powered engines, on the basis of the revised emission factors, is calculated to 3,642 tonne of CO, 4,694 tonne of NO_X, 14,787 tonne CH_4 and 3,327 tonne NMVOC in 2005[10]. In Table 14, these emission data are compared with total emissions from stationary combustion plants. It appears that the CH_4 emission from gas engines comprises 65% of the total emission from stationary combustion plants, but the share for NMVOC is 14% and that for NO_X is 7%.

The Danish emission inventory for CH_4 from stationary combustion is 7% lower with the revised emission factors. The change for the other emissions is more limited as the share of the total emission which stems from gas engines is lower.

Table 14 Total emission contribution from Danish gas engines, 2005[3)]

	CO [tonne]	NO_X [tonne]	UHC [tonne (C)]	CH_4 [tonne]	NMVOC [tonne]
Emission from gas engines 2005	3642	4694	13792	14787	3327
Total emission from stationary combustion plants 2005 according to NERI's reporting in 2007[1)]	274010	68506	-	24527	23614
Total emission from stationary combustions plants 2005 with inclusion of revised gas engine emission factors	272201	67903	-	22869	23252
Change in emission inventory for gas engines	-1809	-602	-	-1658	-362
Gas engines share of the total from stationary combustion[2)]	1%	7%	-	65%	14%

[1)] Refers to the Danish emission reporting for the Climate Convention (Illerup et al 2007), in which the revised gas engine emission factors have not yet been included.

[2)] The share refers to the inventory based on revised emission factors

[3)] In NERI's annual emission inventory the revised emission factors will though first be included fully from 2006 (see page 30).

4.2 Start/stop emission

A considerable share of the gas engine emission stems from the start/stop process, and a part of this lies over and above the emission that would occur as a result of an equivalent gas consumption under full-load operation. The extra emission contribution can in principle be regarded as the potential for emission reduction by means of improving engine regulation under start/stop procedures. As can be seen in relation to NO_x from some engine types, there is on the face of it nothing to stop emission factors being lower under start/stop than under full-load operation. Table 15 shows emissions under start/stop. On page 36 the

[10] NB NERI, in future emissions inventories, will first include the revised emission factors from 2006

potential for emission reductions based on engine suppliers improved engine regulation is reviewed.

Table 15 Total emission contribution from Danish gas engines

	CO [tonne]	NO_X [tonne]	UHC [tonne (C)]	CH_4 [tonne]	NMVOC [tonne]
Emission from gas engines 2005	3642	4694	13792	14787	3327
- of which emission under full-load operation	3389	4558	12969	13905	3129
- of which emission under start/stop	254	137	823	882	199
- of which extra emission under start/stop in relation to full-load operation	161	2	434	466	105

1) Refers to the Danish emission reporting to the Climate Convention (Illerup et al 2007), in which the revised gas engine emission factors have not yet been included.

2) The share refers to the inventory based on revised emission factors

4.3 Time-series 1990-2005

Natural gas consumption in engines was lower in 2005 than in the previous year. This can be the beginning of a trend towards lower operation time which is seen for engines on the spot market and the regulating market. There has been a general decrease in fuel consumption in the production of electricity in 2005 as a result of a lower electricity import, but gas consumption has been rather stable during the period 1998-2004 despite large fluctuations in the export of electricity during this period.

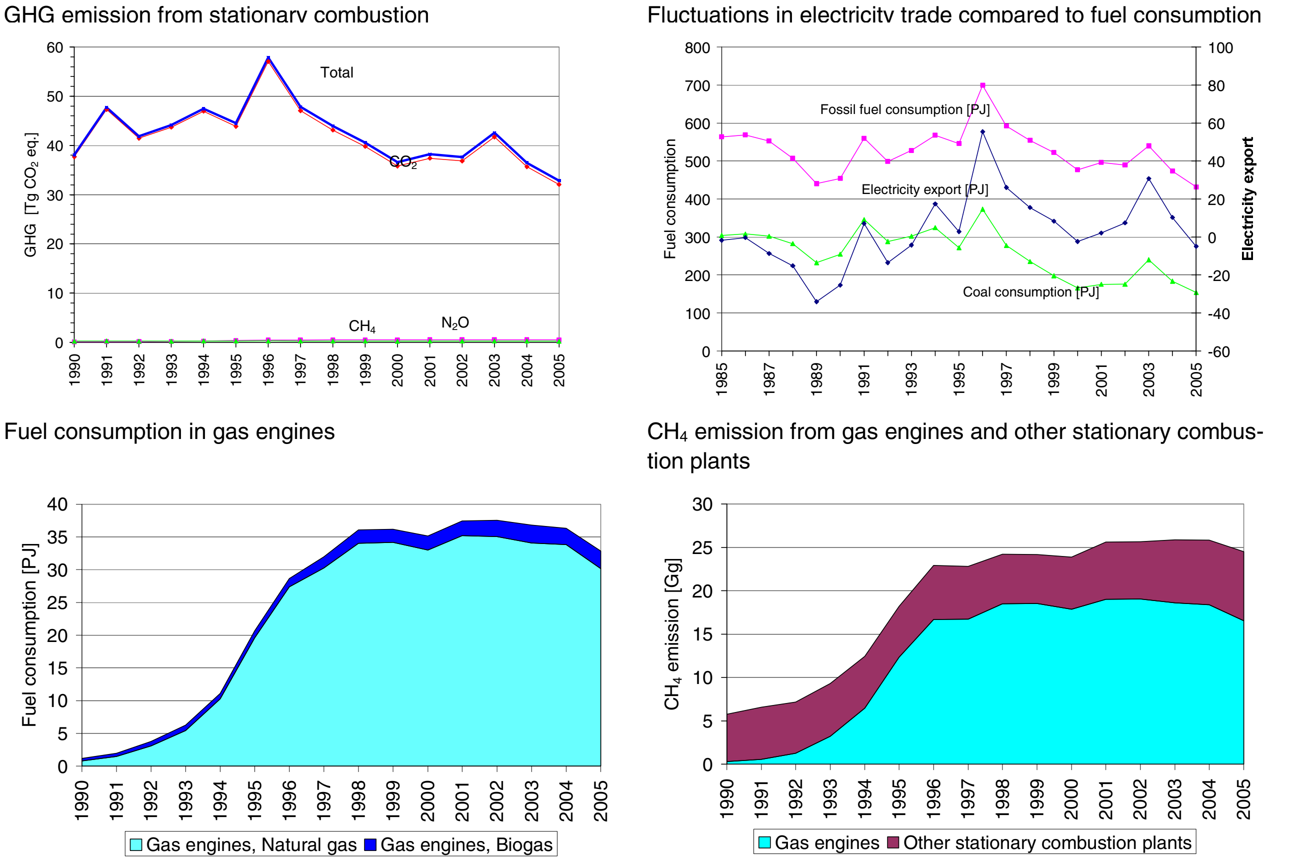

Figure 3 Time-series for emissions from gas engines and stationary combustion plants (Illerup et al 2007)[11]

11 All time-series data is based on the gas engine emission factors previously used.

5 Modified engine regulation under start/stop

The participating engine suppliers have, after reviewing the preliminary 12 emission measurements under start/stop processes, modified the control systems of the engines in order to reduce start/stop emissions. Originally, experiments involving modification of engine regulation were planned for 4 engine types: Rolls Royce, Wärtsilä 34, Jenbacher 300 and Caterpillar 3500. Engine modifications have, however, only been carried out for Rolls Royce and Wärtsilä 34. The work with the Caterpillar engine has not been completed as Pon Power left the project.

For the Rolls Royce engine, measurements have been made for several different modifications as described in sub-report 2 (Jensen, 2006). The measurements included below relate to modification 1.

5.1 Correction factors and emission factors

Correction factors for start/stop emissions, before and after implementation of engine regulation improvement, are shown in Table 16. The correction factors have been calculated according to pattern of operation, based on the census data from the Electricity and Heat Production Survey . In addition, the corresponding dataset for 16-hours' full-load operation and a cold start per day are shown.

It appears that for Rolls Royce the extra UHC emission contribution associated with the start/stop processes fell from 7% to 1%, while the extra UHC emission contribution for the Wärtsilä 34 engine fell from 2% to 1%. The changes are smaller for CO and NO_X.

Table 16 Correction factor for full-load emission factor

	Pattern of operation based on the Electricity and Heat Production Survey			Assumed 16 hours full-load operation and 1 cold start per 24-hour period		
	CO	NO_X	UHC	CO	NO_X	UHC
Rolls Royce before engine modification	1.04	0.99	1.07	1.03	0.99	1.05
Rolls Royce after engine modification [1)]	1.00[1)]	1.00	1.01	1.00[1)]	1.00	1.01
Wärtsilä 34 before engine modification	1.02	0.99	1.02	1.01	0.99	1.01
Wärtsilä 34 after engine modification	1.01	1.00	1.01	1.01	1.00	1.01

1) CO catalytic converters were fitted on the Rolls Royce engine between the two measurement rounds. This can affect the results.

Emission factors for Rolls Royce and Wärtsilä 34 are shown in Table 17.

Table 17 Revised emission factors (incl. start/stop contribution)

	Pattern of operation based on the Electricity and Heat Production Survey		
	CO [g/GJ]	NO_X [g/GJ]	UHC [g/GJ]
Rolls Royce before engine modification	70	154	518
Rolls Royce after engine modification	68	156	489
Wärtsilä 34 before engine modification	110	136	409
Wärtsilä 34 after engine modification	109	137	407

5.2 Emission reductions

Under full implementation of the modified engine regulation at Rolls Royce and Wärtsilä 34, the annual emission of CO from Danish gas engines will fall 1%, UHC will fall 2% and NO_X will rise by 0.5%.

If it is assumed that the start/stop correction factors for all engine types are reduced so the highest are the same as those for the modified Rolls Royce or Wärtsilä 34 engines, the Danish gas engine emission of CO could be reduced by 4%, UHC by 2%, while the NO_X emission would remain practically unchanged. That the reduction of the UHC emission is not larger is because the start/stop correction factor for the majority of the other engine types already lies below or at the same level as that achieved for the Rolls Royce and Wärtsilä 34 engines.

The emissions and emission reductions calculated are shown in Table 18. In Table 19, the emission reduction is compared with the total emissions from stationary combustion plants. The potential for reduction of the CH_4 emission corresponds to approx. 1.2% of the total emission from stationary combustion if just Rolls Royce and Wärtsilä 34 engines are modified. If the other engine types are modified too, so that the start/stop correction factor, as a maximum, lies at the same level as for these two engine types, the potential is 1.4% of the total emission from stationary combustion. For CO, NO_X and NMVOC, the reduction is less as smaller amounts of the total emissions stem from gas engines.

Table 18 Total Danish gas engine emission 2005 with improved engine regulation

	CO [tonne]	NO_X [tonne]	UHC [tonne]
Emission without engine modification	3642	4694	13792
Emission with engine modification for Rolls Royce and Wärtsilä 34	3606 (-37) (-1%)	4716 (+21) (+0.5%)	13527 (-265) (-1.9%)
Emission engine modification for all engines that lie over Rolls Royce's / Wärtsilä 34's correction factor level	3507 (-136) (-4%)	4699 (+5) (+0.1%)	13497 (-295) (-2.1%)

Table 19 Gas engine emission compared with total Danish emissions

	CO [tonne]	NO_X [tonne]	CH_4 [tonne]	NMVOC [tonne]
Emission from gas engines 2005	3642	4694	14787	3327
Total emission from stationary combustion plants 2005 according to NERI's reporting in 2007[1)]	274010	68506	24527	23614
Total emission from stationary combustion plants 2005 with inclusion of the revised gas engine emission factors	272201	67903	22869	23252
Total emission from stationary combustion plants 2005 with inclusion of the Rolls Royce + Wärtsilä 34 modifications	272165 (-0.01%)	67925 (+0.03%)	22585 (-1.2%)	23188 (-0.3%)
Total emission from stationary combustion plants 2005 with inclusion of the engine modifications equivalent to those made for Rolls Royce/Wärtsilä 34	272102 (-0.04%)	67887 (-0.02%)	22553 (-1.4%)	23181 (-0.3%)

[1)] Refers to the Danish emissions reporting to the Climate Convention (Illerup et al 2007), in which the revised gas engine emission factors have not yet been included.

5.3 Implementation of engine modifications

The engine suppliers have communicated that the improvements in engine regulation developed during the project will not be implemented in future. This is because the existing engines comply with the start times that are required to offer regulating power and no environmental requirements exist, which could make implementation necessary (Jensen, 2006).

6 Projections

6.1 Emission factors

Trading arrangements in relation to the spot market, regulating power or reserve power will potentially result in changes in emission factors in future. The aggregate Danish full-load emission factors as well as the start/stop correction factors may undergo changes.

6.1.1 Full-load emission factors

The distribution of the consumption of gas according to engine type can be shifted as all plants larger than $5MW_e$ per 1 January 2007 convert to market pricing (spot/regulating/reserve). As a result, approx. 50% of the installed engine capacity now operates under market conditions, and the number of hours of operation for the engines associated with this capacity may, depending on price developments, change considerably. The changed distribution of gas consumption among the individual plants could be thought in itself to change the aggregate full-load emission factors. The share of large pre-combustion engines is expected to be higher for the plants in the liberalised market than for the smaller plants that continue to be priced according to the three-part tariff.

An analysis of data shows that the CO and NO_X emission factors[12] for the group of engines that per 1 January 2007 operate on the liberalised market are 10% lower than the factors for engines on the three-part tariff. The UHC emission factor[12] is 23% higher for engines on the liberalised market than for engines on the three-part tariff. Figure 4 shows the Danish full-load emission factors under various assumptions regarding production downturn for plants > $5MW_e$. Full-load emission factors for CO and NO_X are up to 2% higher in the case of a halving of production in plants on the liberalised market, while the UHC emission factor will fall 3%. The full-load factors are therefore not especially sensitive to variation in the production conditions of liberalised plants.

[12] Full-load emission factors

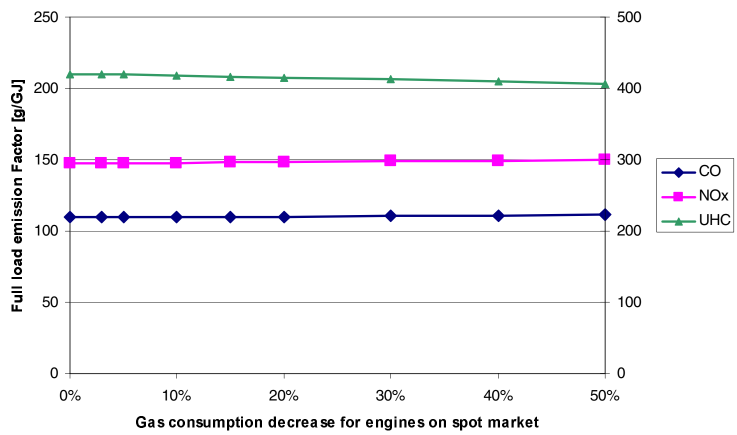

Figure 4 Full-load emission factors sensitivity to production downturn at liberalised plants

6.1.2 Correction factors for start/stop

It appears that conversion from the three-part tariff to the spot market or the regulating market has to date not significantly changed the number of hours of operation per start and, in turn, the correction factors for the emission factors. That price developments in future, however, may change the number of hours of operation per start and thereby the start/stop correction factors, cannot be rejected.

6.2 Energy projections

Fuel consumption in engines may, on conversion to the liberalised market, vary a great deal from year to year. From 2007, 50% of the installed gas engine capacity operates on the liberalised (spot, regulating power or reserve power). The liberalised plants can change between pricing arrangements according to price fluctuations in electricity and gas. Energy projections will therefore be far more uncertain than previously.

DGC's data collection for this project indicates that the number of hours of operation for plants operating according to the three-part tariff on average is approx. 10.4 hours/day, and according to the spot market on average approx. 7.2 hours/day. This is equivalent to a 31% lower operation time on the spot market. DGC's data also indicates the number of hours of operation for regulating power of 1.4 hours/day (average) equivalent to an operational downturn of 87%.

NERI's emission projections are based on energy projections from the Danish Energy Authority in which gas engine consumption is not specified. NERI has for each branch determined aggregate emission factors (implied emission factors) on the basis of various assumptions concerning the composition of technology.

Energinet.dk similarly prepares emission prognoses. These are calculated for two energy price projections; a high and a low price sequence. Energy production from gas engines is not specified, but in high as well as low price sequences, the CH_4 emission lies at the same level as in 2004. This may indicate that a large decline in actual production from engines has not been included in the calculations.

Energinet.dk takes spot market arrangements into account in their prognoses, while system services – incl. regulating power and reserve power – are not included in their model calculations (Schougaard 2007). Some system services, including regulating power and reserve power, are associated with a lower number of hours of operation while others are associated with higher numbers (Schougaard 2007).

Energinet.dk includes high-price level production at plants operating according to the spot market as just as high as under the three-part tariff. At low-price levels, the production from engines on the spot market is calculated 50% lower, and production for engines operating with the three-part tariff 10-15% lower, than under high-price levels (Schougaard 2007).

NERI's overview shows that approx. 50% of the gas engine capacity is in the liberalised market. Therefore, in using energy production data from Energinet.dk the output from gas engines under the low-price levels will be seen overall to be 30-35% lower than with high price levels /the three-part tariff.

Energinet.dk's input data (price level and consumption projections) for prognosis calculations are coordinated with the Danish Energy Authority.

Wärtsilä and Rolls Royce have contributed with data on the number of hours of operation. Data from Wärtsilä is shown in Table 20. These data show that the number of hours of operation under liberalised market conditions have been between 8% higher and 45% lower than those under the three-part tariff. A very large disparity in the hours of operation is therefore apparent.

Table 20 No. of hours of operation aggregated from the Wärtsilä dataset

Year	2000	2001	2002	2003	2004	2005	2006	2007
								1st quarterx4
All pricing systems	13.7	13.3	10.9	10.9	10.8	10.4	7.7	8.2
Three-part	13.7	13.3	10.9	10.9	10.8	11.1	7.3	12.4
Market pricing	-	-	-	-	-	9.2	7.9	6.8

Rolls Royce has noted a production downturn of approx. 21% from 2004 to 2006. This dataset is though not divided up according to trading arrangements. A marked fall in the number of hours of operation in 2007 is evident.

6.2.1 Overall view

Projection of consumption in gas engines falls outside the scope of this project, but the results of the project underline that improved data in this area could be of relevance. It can be concluded that Energinet.dk's prognoses calculation for low-price sequences accord reasonably well with data for engines on the spot market collected by DGC and data from the engine suppliers. Under high-price sequences, Energinet.dk does not expect a fall in production. System services are not as yet included in the energy projections.

6.3 Scenarios

In contrast to the emission factors, which can be expected to be stable, a fall in the number of hours of operation, and thereby natural gas consumption in the engines, is expected in years to come. As the CH_4 emission from gas engines is a rather important source this is likely to be expressed in the Danish emission inventories – primarily for the sectors under stationary combustion.

In order to illustrate this, four scenarios are considered below. Scenarios 1 and 2 are based on number of hours of operation from this project. Scenarios 3 and 4 are based in Energinet.dk's price scenarios. The scenarios are as follows:

- Scenario 1: All engines convert to the spot market with an annual number of hours of operation of 2,633 hours
- Scenario 2a: All plants > $5MW_e$ convert to the spot market with 2,633 annual hours of operation. All plants under $5MW_e$ stay on the three-part tariff with 3,792 annual hours of operation.
- Scenario 2b: All plants > $5MW_e$ convert to the regulating power market with 500 annual hours of operation. All plants under $5MW_e$ remain in the three-part tariff with 3,792 annual hours of operation.
- Scenario 3: All plants > $5MW_e$ convert to the liberalised market under the spot market and production data is assumed to be according to Energinet.dk's low price scenario, i.e. with a production downturn of 30-35% (three-part tariff -12%, spot -50%).
- Scenario 4: All plants > $5MW_e$ convert to the liberalised market under the spot market and production data is assumed to lie between Energinet.dk's low- and high-price scenarios, i.e. a production downturn of 15-17.5% (three-part -6%, spot -25%).

Introduction of new engine types is not taken into consideration, nor are any increases in production at other plant types. In scenario 1 and 2, any price developments that would lead to changes in the number of hours of operation for the individual trading arrangements are not taken into consideration.

Scenario 4 builds on what would appear to be the best available dataset. Here, however, only conversion to the spot market is included, while conversion to regulating power/reserve power is not.

The emissions associated with the four scenarios are shown in Table 21. The scenarios show a fall in the CH_4 emission of 0.7-2.5% of the total Danish CH_4 emission. Also, the total Danish NO_X emission changes significantly with a fall of 0.3%-0.9% in the four scenarios. For the CH_4 emission, even if production increases in other plant types, a fall in the CH_4 emission will occur and the CH_4 emission factor for gas engines is markedly higher than for other plant types.

If stationary combustion is looked at in isolation, a fall in the CH_4 emission of 8-28% is seen in the four scenarios.

Table 21 Scenarios for changes in operation[1)]

	CO	NO_X	UHC	CH_4	
Gas engine emission total					
Scenario 1	2674	3395	10030	10754	tonne
Scenario 2a	3347	4208	12108	12981	tonne
Scenario 2b	2378	2952	7722	8279	tonne
Scenario 3	2629	3361	9481	10165	tonne
Scenario 4	3142	4028	11656	12497	tonne
Revised 2005 inventory	3642	4694	13792	14787	tonne
Change in relation to the revised gas engine inventory 2005					
Scenario 1	-27%	-28%	-27%	-27%	
Scenario 2a	-8%	-10%	-12%	-12%	
Scenario 2b	-35%	-37%	-44%	-44%	
Scenario 3	-28%	-28%	-31%	-31%	
Scenario 4	-14%	-14%	-15%	-15%	
Change in total emission from stationary combustion					
Scenario 1	-0,4%	-1,9%		-18%	
Scenario 2a	-0,1%	-0,7%		-8%	
Scenario 2b	-0,5%	-2,6%		-28%	
Scenario 3	-0,4%	-2,0%		-20%	
Scenario 4	-0,2%	-1,0%		-10%	
Change in total Danish [1)]					
Scenario 1	-0,2%	-0,7%		-1,5%	
Scenario 2a	0,0%	-0,3%		-0,7%	
Scenario 2b	-0,2%	-0,9%		-2,5%	
Scenario 3	-0,2%	-0,7%		-1,8%	
Scenario 4	-0,1%	-0,4%		-0,9%	

[1)] All data are compared with an inventory for 2005 based on the revised emission factors

7 Conclusion

Revised emission factors have been prepared for Danish gas engines in which emissions under start/stop processes are included. The revised emission factors are: CO 115 g/GJ, NO_X 148 g/GJ, UHC 434 g (C)/GJ, CH_4 465 g/GJ and NMVOC 105 g/GJ. The correction factors that include the start/stop emissions in the calculations are determined at 1.05 for CO, 1.00 for NO_X and 1.03 for UHC.

The emission factors calculated are lower than the emission factors used to date, which alone were based on full-load operation. This is due to a partial updating of the full-load emission factors, which have fallen in recent years. Revised full-load emission factors are estimated for the various engine types based partly on new emission limit values as well as on measurement reports from a wide range of engines. It can be expected that a measurement programme for all larger engine types will provide a far better estimate of the aggregate Danish full-load emission factors. The full-load factors are expected at the moment to be overestimated for several engine types where the emission limit values are used as emission factor.

The total emission contribution from Danish natural gas driven engines for 2005 is calculated to 3,642 tonne CO, 4,694 tonne NO_X and 13,792 tonne (C) UHC (comprising 14,787 tonne CH_4 and 3,327 tonne NMVOC). As a result, the CH_4 emission from engines constitutes 65% of the total emission from stationary combustion plants, whereas the share for NMVOC is 14% and the NO_X share is 7%.

Rolls Royce and Wärtsilä have carried out experiments with modification of engine regulation under start/stop with the aim of reducing the associated emission contribution. For both manufacturers the emission contribution under start/stop has been reduced for CO and UHC, while the NO_X emission contribution has risen slightly.

Under full implementation of the engine modifications for the Rolls Royce and Wärtsilä 34 engines, the annual emission of CO would fall by 1%, UHC by 2%, while NO_X would rise by 0.5%. If it is assumed that the start/stop correction factors for all engine types are reduced so the highest correction factors are the same as those for the revised Rolls Royce or Wärtsilä 34 engines, the Danish gas engine emission of CO could be reduced by 4%, UHC by 2%, while the NO_X emission would remain practically unchanged. Rolls Royce and Wärtsilä have, however, both communicated that the engine modification will not be implemented as the existing engines comply with the start times required to offer regulating power, and as environmental requirements are not in force, which could make such implementation necessary.

The most important environmental change in converting to trading arrangements in the liberalised market is not the change in the emission factors associated with the gas engines, as the number of hours of operation per engine start has shown itself to be rather constant. On the other hand, variability in the annual number of hours of operation as a result of price developments for electricity and gas will be expressed in emission totals, so that in future greater deviation in the contribution to emissions from gas engines can be expected from year to year. Under a high-price scenario, large deviations in the number of hours of operation is expected and emission contribution in relation to the situation to date. Under a low-price scenario the number of hours, and thereby the emission contribution, can be expected to fall considerably.

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Annex 1: Selection of plants for measurement

Selection of engine types for emission measurement and modification

In connection with the Eltra PSO project 5738 *Start hurtigere med mindre emission* ('Start quicker with less emission'), NERI will be selecting eight engine types for which to measure start/stop emissions and a further four engine types for measurement and further development of start/stop processes. The selection procedure must ensure that the engine types that are measured provide a good representation, energy-wise, of the capacity installed in Denmark.

Background to the data

The determination of which engine types for which start and stop emissions measurement should be selected, and for which four engines, further work should be carried out in relation purely to engine development, is based on a database of natural gas driven engines in operation in Denmark in 2004. Preparation of this database has been based on the following data sources:

- Danish Energy Authority's energy producer census Electricity and Heat Production Survey 2004
- Database of decentralised CHP plants prepared under the project Eltra PSO 3141
- DGC's overview of gas engine types installed in Denmark
- Contributions from the participating engine suppliers

The Danish Energy Authority's Electricity and Heat Production Survey includes all electricity and/or district heat producing units in operation in Denmark in 2004. The energy Electricity and Heat Production Survey is not published, but the Danish Energy Authority has made the census data available for this project. NERI has extracted data which includes natural gas powered and partially natural gas powered engines. The Electricity and Heat Production Survey covers engine level e.g. plant and equipment/system ID, electricity capacity, heat capacity, natural gas consumption in 2004 and electricity production in 2004. Moreover, the census data contains engine makes and types.

In connection with Eltra PSO project 3141, a database was prepared for, among other things, natural gas-powered engine make and engine type in the year 2000. The database has not been published, but the project partners have made the database available for this project. In connection with Eltra PSO 3141, the engine types were grouped into engine types that construction-wise and emission-wise can be regarded as being the same, i.e. same engine design but, for example, with a different number of cylinders. These engine groups are re-used with a small number of updates. Eltra PSO 3141 also included coupling of engine data with data from the Electricity and Heat Production Survey, and it has been possible to take this coupling forward in a simple continuation, coupling the collected engine data to the energy producer census data for 2004.

DGC has, on the basis of their overview of gas engines, provided supplementary information for plants where data was missing from the other sources.

Finally, the participating engine suppliers have contributed to the list.

Gas engines in operation 2004

Based on the database for gas engines in operation in Denmark in 2004, an overview of the natural gas consumption of the various different engine makes and engine types has been prepared.

Figure A1.1 shows the consumption of natural gas according to engine make. Four makes dominate in Denmark: Rolls Royce (formerly Ulstein Bergen), Caterpillar, Jenbacher and Wärtsilä. Consumption of natural gas among these four constitutes 87% of the total consumption in gas engines in 2004 – or 88% of electricity production from gas engines.

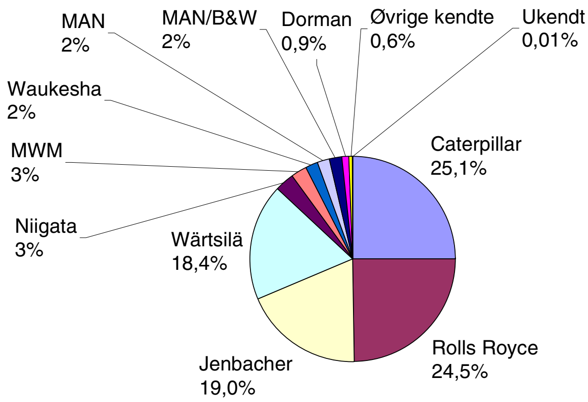

Figure A1.1 Natural gas consumption 2004 distributed according to engine make

Figure A1.2 shows the consumption of natural gas in 2004 according to engine type (grouped). Only the most important engine types are shown in the figure – complete data is shown in Table A1.1.

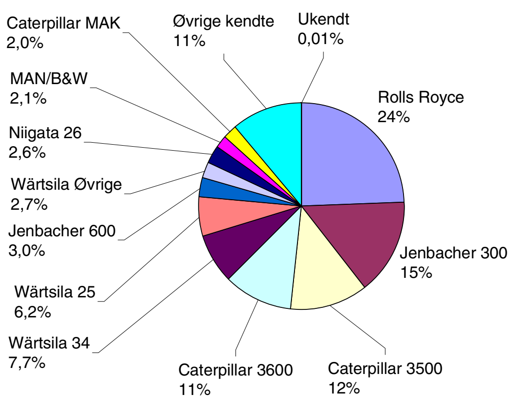

Figure A1.2 Natural gas consumption 2004 distributed according to engine type (grouped)

Table A1.1 Emission measurements distributed according to engine type

Make	Engine group	Natural gas consumption [TJ]
Rolls Royce	Rolls Royce	8663
Jenbacher	Jenbacher 300	5259
Caterpillar	Caterpillar 3500	4355
Caterpillar	Caterpillar 3600	3753
Wärtsilä	Wärtsila 34	2734
Wärtsilä	Wärtsila 25	2186
Jenbacher	Jenbacher 600	1061
Wärtsilä	Wärtsila Other	943
Niigata	Niigata 26	934
MAN/B&W	MAN/B&W	747
Caterpillar	Caterpillar MAK	706
Waukesha	Waukesha	661
MAN	MAN	645
Wärtsilä	Wärtsila 28	639
MWM	MWM TBG 604	572
Dorman	Dorman	332
Jenbacher	Jenbacher 400	313
MWM	MWM TBG 620	289
Niigata	Niigata 33	139
Jenbacher	Jenbacher 200	76
FRICHS	FRICHS mini	65
Guascor	Guascor	38
Perkins	Perkins	37
Caterpillar	Caterpillar 33-3400	30
MWM	MWM G232&234	29
TOTEM	Totem	23
IVECO	Iveco	23
Polo	Polo	15
Scania	Scania	9
TMW	TMW	7
Nedalo	Nedalo	5
Køhler&Ziegler	Køhler&Ziegler	4
Dynaf	Dynaf	1
FORD Power Torque	FORD Power Torque	0.3
Unknown	Unknown	5
Total		35297

The relative number of engines fitted with an oxidation catalytic converter is rising, as a greater number of engine types now are fitted with oxidation catalytic converters to comply with the new emission limit valid from October 2006. Catalytic converter data is however not included in the engine database as yet. DGC will at a later time collect data for engines fitted with a catalytic converter, including type. These data will subsequently be included by NERI in the engine database, so the data can be included in the start/stop emission calculations.

Criteria for plant selection

A range of criteria and specifications have been put forward in connection with selection of engine type for measurement /development:

Selection needs to secure good energy coverage for the installed gas engine types.

In order to cover a broad spectrum of engine types a maximum of three measurements are performed for each engine type. The extra knowledge gained in relation to a fourth measurement is regarded as being limited.

Existing start/stop measurements are involved in the results, but NERI has chosen to disregard the existing measurements in connection with selection. This decision is justified as most of the existing start/stop measurements are significantly less comprehensive than the measurements that will be carried out in this project.

A range of engine suppliers are in the process of carrying out modifications of engines and/or installing catalysts in order to comply with Bekendtgørelse 621 from 2005, which provides new emission limits for existing engines from 2006. Where modification will include all engines within a group of engine types, the measurements are to be made on an engine which has already been modified and is representative for the group from 2006.

NERI designates the 12 engine types that will be measured, but selection of actual plants and engines is left to DGC in collaboration with the relevant engine supplier. They are responsible for ensuring that the engine is representative for the engine type from 2006, i.e. they vouch that the engines in question do not comprise experimental plant, plant with improved regulation or flue gas cleaning technology, or similar, compared with the other engines in the group.

Engine types where measurements are to be made (12 measurements)

Measurements are required for 12 engines. From the gas engine database 10 engines are selected based on a criterion that one measurement is made for each 6% of the gas consumption in 2004. A maximum of three measurements, however, per engine type are made. The 10 measurements are distributed in this way.

For the last two measurements a more individual evaluation is made. On the basis of an energy consideration, a Caterpillar 3600 and a Jenbacher 600 have been selected. Several engine types have almost the same consumption as Jenbacher 600, but for various reasons are less interesting:

Jenbacher 300, remaining consumption when 2 x 6% has been deducted. As there are already two measurements, this option has been disregarded.

Niigata 26. Several Niigata 26 engines have been taken out of operation during 2004 and 2005, and the engine type will thereby be of less importance in future.

Wärtsilä Other engine types. This is a collection of different Wärtsilä engine types and the group is therefore not uniform.

The engine types which are not represented in the measurement programme individually represent less than 2.6% of consumption. Altogether, they constitute 21% of consumption. However, a less uniform group of pre-combustion chamber, open chamber and very small engines is involved.

Table A1.2 Emission measurements according to engine type

Engine type	% of consumption	Number of measurements
Rolls Royce	25	3
Caterpillar 3500	12	2
Caterpillar 3600	11	2
Jenbacher 300	15	2
Wärtsilä 25	6	1
Wärtsilä 34	8	1
Jenbacher 600	3	1

Engine types for further development (4 engines)

Four different engine types are required to be selected for further development. The engine types that have the largest share of consumption are Rolls Royce (25%), Jenbacher 300 (15%), Caterpillar 3500 (12%), Caterpillar 3600 (11%) and Wärtsilä 34 (8%). Engine development is carried out on the Rolls Royce, Jenbacher 300, Caterpillar 3500 and Wärtsilä 34 engines. Two open chamber engines are represented, and this would appear reasonable when looking at the distribution of the consumption of gas between pre-combustion chamber engines (64%) and open chamber engines (36%). Furthermore, consideration is given to that all the engine suppliers participating in the project are represented.

Annex 2: Environmental economics - Start-stop project

Research note concerning: Use of environmental economic valuation to estimate damage costs for air emissions in technology assessments

1 Introduction

The choice between different technological solutions is often associated with differences in costs but also differences in associated environmental impact, e.g. in the form of changes in emissions. Application of environmental economic valuation methods to these emissions, however, can improve the basis for decision-making. Establishing damage costs for emissions demands a range of modelling processes from those involving dispersion and exposure to those determining actual damage (often increased mortality or morbidity). This research note describes how these damage costs, whose use is normal practice in Denmark and the EU, are produced for three different emissions types: NO_X, NMVOC and methane. As a practical example, emissions from three different types of gas engine, Ulstein Bergen, Cat 3600 and an average Danish natural gas powered engine are measured, on the basis of emission factors published in Nielsen and Illerup (2003).

This research note describes first, in Section 2, the modelling process itself, from dispersion to exposure and determination of the physical impacts of air pollution. Section 3 summarizes the fundamental elements in the various valuation methods used to assign prices to the resulting physical effects. In most cases increased mortality constitutes the major part of the physical effects. Therefore, a separate section, Section 4, has been included where the two different methods for valuing a statistical life are briefly described.

2 Cause-and-effect chain – relationship between the emissions and the physical effects

Damage from air pollution is determined by means of a cause-and-effect chain, also often termed an 'impact pathway method'. This cause-and-effect chain is illustrated in Figure A2.1. In the cause-and-effect chain the physical effects of air pollution are estimated, e.g. soiling and corrosion of buildings, forest dieback, and increased mortality and morbidity. The method itself consists of three stages, starting with determining the emission levels by means of emission factors. Second, an average exposure for the population or area concerned is calculated. And finally total health-damaging or material-damaging effects are calculated on the basis of studies which have established a link between exposure and response (e.g. epidemiological studies).

The cause-and-effect chain is based on a range of simplifying assumptions and generalisations at each stage, from determination of the emission factors to exposure and dose-response functions and on to the final valuation of damages. The individual results are thereby associated with a smaller or greater measure of uncertainty.

Models are used to calculate the dispersion and transformation of the emissions. Over short distances, the models include parameters such as distance from source, emission height, wind speed and direction, turbulence and topography. Chemical reactions have no significance over short distances. For distances over and above 50 km, however, transformation processes are included, together with wind speed and direction, as well as the speed with which aerosols and particles are deposited. Distinction is therefore made between primary emissions and secondary emissions which are first formed via chemical processes in the atmosphere through reactions between one or more pollutants. For NO_X and VOC it is primarily their secondary products, nitrate aerosols and ozone (for NO_X) and ozone (for VOC) which are relevant for the final damage estimate due to the associated health-damaging effects (see Table A2.1). As these secondary products are formed and disperse over wider distances, it is assumed that there is no difference between local and regional effects, i.e. population density at the source of the emission is irrelevant. The models produce dispersion factors (ug/m^3 per tonne/year) for a geographic area (divided into quadrants) and these dispersion factors are converted into population exposure factors by multiplying population by dispersion factor for each quadrant.

The relationship between exposure to the population and damage is described in terms of a dose-response relationship, as this establishes a relationship between a certain pollution level (dose) and the corresponding physical effect (response). This function thereby does not comprise a valuation method in itself, but its results are a necessary condition for valuation methods to be used to describe the physical damage effects in monetary terms. By dividing the value of the total physical damage effect by the amount of the emission concerned an emission cost on a per tonne basis can be obtained.

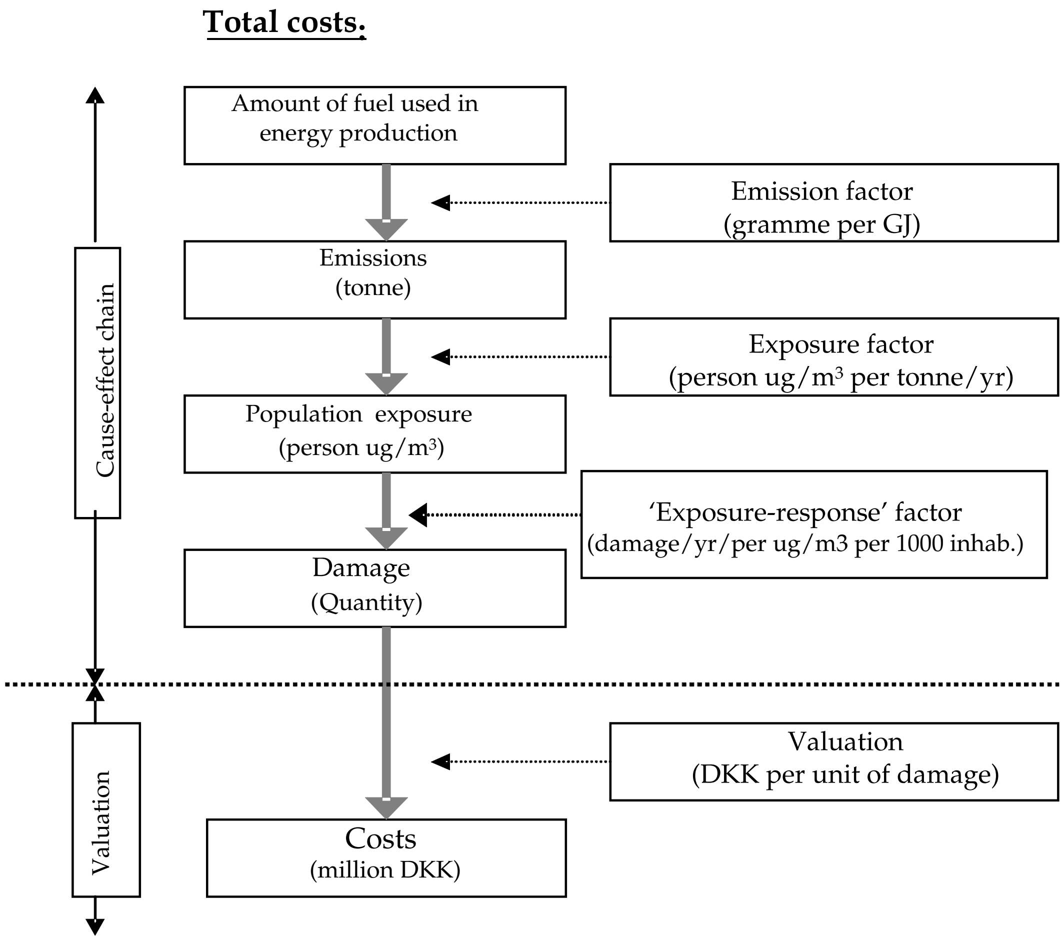

Figure A2.1 Operational cause-effect chain between emissions and costs
Source: Færdselsstyrelsen (2001), p.8, adjusted for energy-producing plant

Table A2.1 Health and environmental effects of various emissions

Pollution-factor	Mechanism	Receptor					
		Climate	Health	Crops	Forest	Fishery	Buildings
NO_X	Direct		+				
	Aerosols	?	+				
	Acidification				+	?	+
	Via ozone	?	+	+	?		?
NMVOC	Direct		?				
	Via ozone	+	+	+	?		?
CH_4	Greenhouse direct	+					

+ Effects which have been valued
? Effects which have been identified but which are too small, too difficult to estimate, or too uncertain to be used as input to valuation
Source: Eyre et al. (1997), p.11.

3 Valuation of damage from air pollution

Valuation of the external effects of air pollution can contribute to internalisation of these effects in the decision process. Valuation can be used as input to cost-benefit analyses or form the basis for determining the level of a tax, e.g. for NO_X or SO_2 emissions. Environmental economics has for many years developed and employed various methods for assigning values to environmental effects for which prices determined by the market do not exist. The problem is, however, that there is often a high degree of uncertainty linked with valuation studies and their results. Performing a valuation exercise is an expensive undertaking and therefore in many cases values may be transferred from other – Danish but also foreign – valuation studies in order to assess these external effects. This is known as 'benefit transfer'.

The various valuation methods are explained in a range of publications such as Freeman III (2003) and Møller (1996), and with focus on the empirical challenges in Champ et al. (2003), and Haab and McConnell (2002). The methods are briefly described below. Generally, valuation methods are divided into the categories 'direct' and 'indirect'. Direct methods ('stated preference methods') measure people's preferences by placing them in choice situations in hypothetical markets, while indirect methods ('revealed preference methods') attempt to extract preferences by looking at people's actual choices in related markets. In relation to valuation of damage from emissions it is mainly the direct methods which are of relevance; therefore indirect methods are not described in such detail. As an alternative to preference-based methods, a range of cost-based methods such as prevention and treatment methods, and shadow price methods exists.

Direct valuation methods ('Stated preference methods')

In direct valuation methods, a hypothetical market is created where people are asked about their willingness to pay (WTP)[13] to achieve an environmental improvement or alternatively their 'willingness-to-accept', i.e. the compensation they would demand in connection with a deterioration in environmental quality. For determining the value of the external effects of energy production the method is especially relevant for valuation of a statistical life (here, the WTP for a reduction in mortality risk) and increased morbidity risk (illness).

Contingent valuation

The hypothetical valuation method most commonly used is contingent valuation (CV), where questionnaire-based study data is collected on how much people are willing to pay for a hypothetical change in quantity of a given environmental good. A typical CV study is comprised of 3 elements: a description of the scenario, i.e. the hypothetical market situation the respondent is supposed to be in; questions to determine the price the respondent is willing to pay, and a number of questions concerning specifics relating to the respondent (income, education, place of residence, family status).

In using the CV method, it is not only important that respondents have sufficient knowledge of the good, but also how the potential financing associated with the good will take place. This can for example take the form of taxes, charges, cuts in other budgets or possibly, for example, an access fee to a certain recreational area.

[13] 'Willingness-to-pay' will be used below in its abbreviated form, 'WTP'.

In a CV study, various types of systematic error can occur which should as far as possible be avoided through the way in which the questions are formulated and the description of the valuation situation. Strategic error can for example occur if respondents do not have an incentive to reveal their true preferences, e.g. because they reckon that a public good will be offered anyway and that they – by giving a lower WTP – could avoid paying so much. A problem can also lie in the design of the questionnaire itself, e.g. because the choice of WTP method influences the level of the WTP responses. Generally it is often a problem that respondents, due to the hypothetical nature of the situation do not take into account their budget restrictions, i.e. they do not consider that the environmental good in question will mean a reduction in consumption of another good.

Choice Experiments

Instead of contingent valuation, more and more choice experiments have been carried out in recent years, where respondents, rather than answering a single question, are required to consider choice options, termed 'choice sets'. Choice options within each choice set are different in terms of their attributes and the price which is to be paid for each good. The choice situation is therefore more reflective of the types of choices respondents are faced with from day to day, e.g. in the supermarket or dealings with other businesses. On the basis of the choices made, the WTP for the individual attributes can be estimated.

Indirect valuation methods ('Revealed preference methods')

Hedonic valuation

The underlying idea behind the hedonic method is that the consumers, through their choice of consumer goods in a well-balanced and undisturbed market, maximise their utility. One of the classic examples of such a choice is the house or apartment bought on the property market. Therefore the label the 'house price method' is often used. The price of a house will depend on a range of characteristics. These can be structural characteristics of the house itself, e.g. plot size, number of rooms, heating technology, or the property's surroundings, as well as specific socioeconomic conditions such as environmental and neighbourhood characteristics. Also the location itself, distance to shops and public transport will influence the price. Individuals express their preferences for the good's characteristics by choosing a specific set of these and by paying the corresponding market price. By modelling the price of the house as a function of the different explanatory variables, the marginal WTP can be estimated for a change in the individual characteristics.

Even though the method has the advantage that it is based on actual market behaviour and does not rely on answers given in a hypothetical situation, it is not completely free from problems in all situations. For the property market it is, for example, important that the market is transparent, so all the property's characteristics are observable for the potential buyer and especially the environmental good which is being valued. Similarly, transaction costs of moving house should be limited. It should also be noted that the method can only measure the use value of an environmental good, and also only that relating to properties in proximity to each other.

In the USA, the hedonic method is also used to estimate the value of a statistical life by looking at the differences in wages between places of work which differ according to the degree of risk of suffering injury or illness.

Travel cost method

The 'travel cost method' has been used especially to measure the recreational value of forest, lakes or coastal areas. The idea behind the method is that despite the fact that access to recreational area is free of charge in the majority of cases, visitors to these areas still incur costs in the form of transport expenses and time, which can be interpreted as their willingness to pay for the environmental good in question. The method builds upon the assumption of complementarity between consumption of an environmental good and consumption of market goods; here, a negative correlation between visit frequency for a recreational area and transport costs. Transport costs include the direct costs for e.g. petrol or public transport and time, but also depreciation on the car, as well as any entrance fee to the areas.

On the basis of the number of visits to an area and the costs associated with each visit, as well as household income and any other socioeconomic information, a demand curve for the environmental good can be estimated which can subsequently be used to estimate willingness to pay for the travel destination.

Valuation on the cost side

Prevention and treatment costs

In order to avoid environmentally damaging impacts from certain activities, either prevention costs can arise ('avoidance costs') (e.g. in the form of installation of a catalytic converter to reduce air pollution) or treatment costs ('averting behaviour') (e.g. in the form of medicine to relieve illness). By using the methods in a socioeconomic valuation the implicit assumption is that the marginal costs incurred correspond to the marginal value of the benefits incurred in reducing the negative environmental impact. However, it is not likely that all individuals in all cases will be able to compare the actual damage costs with the costs incurred. Furthermore, in the majority of cases it is not possible to buy units of prevention or treatment on an ongoing basis, e.g. it is an either-or decision to purchase a car with airbag or without, i.e. it is not possible in this case to weigh the marginal costs against the marginal benefits.

Another problem with prevention and treatment equipment or activities is that investments also serve other ends than reducing a particular environmental problem, e.g. investment in air conditioning systems involves temperature regulation as well as tackling air pollution. In relation to the valuation of damage from air pollution, prevention and treatment costs are especially relevant for increased morbidity (illness), soiling of buildings, and activities which are designed to counteract acidification of agricultural and forestry areas.

Shadow price method (valuation on the basis of costs when in the case where environmental goals exist)

In the case where society has adopted a certain environmental goal (e.g. fulfilling the CO_2 reduction laid down in the Kyoto Protocol), the cost associated with the defensive action can be regarded as the socioeconomic price associated with either further negative impact on the environment (because society consumes factors of production to implement the action) or the price of the environmental benefit (if e.g. measures are implemented to reduce pollution which thereby mean that society can avoid using scarce resources in connection with measures to ensure that targets are met). Here, it is assumed that goals mirror the preferences of the society. Therefore, prices described in this way are often termed 'shadow prices', as they only in a very indirect way reflect the price that society is willing to pay for avoiding damage from given types of pollution.

However, what is being valued here are not the environmental impacts, i.e. potential damage, but only the marginal costs of fulfilling the goal. If one wishes to assess whether the actual targets set are optimal from a welfare economic viewpoint, it is however necessary to value the marginal benefits that arise due to the target adopted and compare these benefits with the value of the marginal costs of reaching the goal.

Summary of methods

Table A2.2 Valuation methods and their application

Method	Type of value priced	External effects used for	Comments (advantages, disadvantages, uncertainty, etc.)
Hedonic method	Use values	Change in land use (recreational areas, forest); value of a statistical life;	The advantage is that the method is based on actual market behaviour. The property market, however, needs to be transparent, and transaction costs of moving need to be limited; the owner is possibly not aware of the scale of the noise nuisance. Workers in jobs to which risk is attached can be less risk averse than the average for the population.
Travel cost method	Use values	Change in land use (recreational areas, forest)	Different time values depending on purpose of trip. What is the value of leisure time?
Contingent Valuation)/ Choice experiments	Use and non-use values	Value of a statistical life; increased morbidity (sickness);	Responses can contain different types of systematic error (strategic, design, hypothetical, operational); nesting problems; protest responses.
Prevention and treatment costs	Costs of equipment or action. Costs relate to treatment. Value of production value lost to society.	Increased morbidity (illness); soiling of buildings; acidification of agricultural and forest areas	Individual are potentially not able to compare marginal costs with marginal benefits from investing in prevention or treatment equipment. Equipment can often not be bought continually. Equipment often serves other purposes than helping the specific environmental problem in question.
Shadow price method	Saved or increased costs for society through achieving a certain target.	Air pollution (especially CO_2, SO_2, NO_x)	Targets are not necessarily optimal from a welfare economic viewpoint.

Keywords on benefit transfer

Implementation of valuation studies demands a considerable amount of resources. The transfer of prices from other studies, in time and space, to the policy relevant location presents an alternative to implementation of an independent study. Transfer of values means that monetary values for either environmental benefits or costs calculated for a given location (study site) are transferred to another location, which is termed the 'policy site'. Four types of benefit transfer exist. The simplest is where non-corrected unit values are transferred. Here it is assumed that the welfare gain for the average individual at the policy site is the same as the welfare gain for an average individual at the study site. The problem here is that it is highly probable that there are considerable differences between places both with regard to demographic and socioeconomic characteristics of the affected population. Furthermore, the environmental quality and presence of substitutes can vary between the study site and the policy site.

A better way to transfer values is therefore to adjust the prices so that these reflect the different conditions prevailing at the policy site. A third option is to transfer the benefit (or cost) function itself. A fourth, slightly different, possibility is to use a meta-analysis, where a benefit function is calculated by using regression analyses based on results from a range of empirical studies which investigate the same relevant environmental goods. The validity of benefit transfer has been examined in a number of studies[14], using statistical methods, and the majority of these studies has shown that large uncertainty can be associated with benefit transfer studies (i.e. margins of error of 20-50% or more in some cases) in transferring values from one location to another, even in ideal circumstances.

With regard to assigning values to damage resulting from air pollution, benefit transfer is used for example to estimate values for a statistical life (see following section) for use in the Danish context on the basis of foreign studies, in the absence of original Danish studies on the subject. (The use of a common, European estimate for a statistical life, however, does not take into account ethical questions as, due to their dispersal over long distances, the emissions not only bring about effects in Denmark, but also in neighbouring countries.)

Valuation of a statistical life (VSL[15]) or 'life year lost' (VOLY[16]) is possibly the most discussed and controversial topic in establishing damage costs for emissions; not only because the subject touches upon a range of ethical questions, but also because costs linked to increased mortality comprise a very large share of the costs associated with air pollution. A comparison of different cost-benefit analyses (Eyre et al. (1997); Brouwer and Spaninks (1999)) shows, for example, that health benefits comprise 32-98% of the total benefits of implementation of measures to reduce air pollution. In the section to follow, therefore, a short review of the two main approaches to valuation of increased mortality, VSL and VOLY, is presented.

[14] See Brouwer and Spaninks (1999), p. 96-97 for a summary of the literature in the field.
[15] VSL stands for 'Value of a Statistical Life' and will be used as in abbreviated form from here onwards.
[16] VOLY stands for 'value of a life year' and will be used as in abbreviated form from here onwards for the value of a (lost) life year.

Valuation of a statistical life (VSL)

The term 'statistical life' is used because it is the change in risk of death/mortality and not how much people are willing to pay to avoid their own death which is being valued. The method for valuation of a statistical life builds upon studies of the population's willingness to pay to avoid a specifically-defined increased risk of death. The value of a statistical life saved is calculated thereafter by dividing the individual WTP values by the observed change in the risk to reach WTP per statistical death or – alternatively – by summing the individual WTP declarations until the risk reduction corresponds to a statistical life.

A single example: It is assumed that a specific measure can reduce the risk for a traffic death from four cases per 10,000 to three cases per 10,000. Individuals exposed to this risk are willing to pay on average DKK 100 for this risk reduction (one case less per 10,000). Here the value of a statistical life is kept as DKK 1 million, i.e. DKK 100 divided by 0.0001 in risk reduction – or 10,000 times DKK 100, which is equivalent to a 'whole' statistical life. Here this is expressed in equation form as:

Change in number of deaths per number of individuals:

$$\frac{\Delta mortality}{individuals} = \Delta s$$

Willingness to pay per person for risk reduction:

$$\frac{WTP(\Delta mortality)}{individual} = b$$

Value of a statistical life => $\dfrac{b}{\Delta s} = \dfrac{WTP(\Delta mortality)}{\Delta mortality}$

It is important to understand that nobody is being asked how much they are willing to pay to avoid their own death at a set point in time, but only their willingness to pay for a change in risk. It would be reasonable to suppose that most people would be willing to pay a sum equivalent to their entire fortune to avoid a certain death. Similarly, it is likely that no finite sum of money exists which could compensate an individual for certain death.

Primarily, three methods are used to reveal WTP for a reduction in risk and thereby the value of a statistical life: (1) contingent valuation studies where people are asked directly by means of interview/questionnaire studies about their WTP for a certain risk reduction; (2) hedonic valuation studies, where e.g. differences in salaries for jobs to which risk is attached are looked at; and (3) analyses of voluntarily incurred costs for risk reduction, e.g. in the form of air bags and fire alarm systems.

Valuation of a life year lost (VOLY)

People in different age groups will have different VSL values as the total amount of life years that they might loose differs, i.e. somebody at the age of 80 will have fewer years to loose than somebody at the age of 40. An alternative approach to valuation of mortality resulting from air pollution is to value the period of life time gained by reducing the risk instead of finding the price for a risk reduction itself. This approach to determine the 'value of a life year' is abbreviated to VOLY. The method is based on the assumption that the price for a life year is independent of the individual's age and life expectancy.

Generally speaking, there are two methods to calculate a VOLY. The first and most often used is based on VSL calculations which are converted to values for a life year. The other method is based on questionnaire studies which attempt to find the WTPs expressed in relation to extending the period of life by e.g. one year. The first method regards the value for a life year as equivalent to the annuity which, when discounted over the remainder of the expected lifetime, will be equivalent to the value for a statistical life (VSL). A VOLY is thereby calculated as:

VOLY = VSL * A

A stands for amortisation factor, which is calculated as:

$$A = \frac{r * (1+r)^n}{(1+r)^n - 1}$$

Here, n stands for the number of expected life years remaining and r is equivalent to the discount rate. If the starting point is a fixed VSL, a higher calculation interest means a higher VOLY and vice versa. The VOLY calculation is then used to produce revised VSL (dependent on the number of life years remaining) according to the simple formula:

$$\text{revised VSL (a)} = \sum_{t=1}^{T-a} \frac{VOLY}{(1+r)^t}$$

T is duration of life and a is the age of the victim. T-a represents therefore number of life years remaining. In the formula it is assumed that the VOLY is independent of age. The higher the discount rate r, the lower the value of an age-adjusted VSL. An age-adjusted VSL evidently becomes lower with age and equates thereby maybe more to that one would intuitively expect of age-related WTP declarations. However, no studies are found that support this drastic decline in WTP with age which is assumed in the VOLY method.

4 Unit prices for NO_X, NMVOC and CH_4 used in Denmark

The first large-scale project which attempted to calculate damage estimates in connection with air pollution from energy production for all EU countries was ExternE (CIEMAT (ed.) (1998)). Here, damage costs relating to SO_2, NO_X and particles were estimated. The successor to the project, the CAFE programme (Clean Air for Europe)[17] has updated damage costs for these three substances (although for particles now for $PM_{2.5}$ instead of PM_{10}), and has included damage costs for NH_3 and VOC. In Denmark, an independent analysis of damage costs for $PM_{2.5}$, NO_X and SO_2 was carried out in 2004 (Andersen et al. (2004)).

[17] (see http://ec.europa.eu/environment/air/cafe/general/keydocs.htm for more information)

For the calculations in this research note damage costs from the Danish study for NO_X and from the CAFE programme for VOC are used. For methane, an average quota price for CO_2-equivalents over the last 18 months is used. The content and methodology in the individual studies is described briefly below, as well as the approach for valuation for methane. Unfortunately no reliable prices are found for CO at present. Therefore this emission type is not included in the calculations.

Andersen et al. (2004): Health effects of air pollution – damage costs

The latest Danish estimation of damage costs for emissions is found in Andersen et al. (2004), which used the same model as in Extern E, EcoSense 4.0, for modelling the dispersion of emissions and the resulting exposure of the population resulting from a modern, coal-fired power station situated on Zealand and in West Jutland, respectively. The calculations were, however, only undertaken for $PM_{2.5}$, NO_X and nitrate, and SO_2 and sulphate, not NMVOC and CO, and focus is only upon health effects, i.e. nature and environmental effects such as damage to buildings, are not taken into account. In relation to earlier calculations undertaken on a European level the values for a statistical life and other health effects are transferred to Danish conditions by adjusting them with purchasing power parity-adjusted GNP weights. A value of a statistical life of EUR 1.2 million, i.e. DKK 9 million in 2002 prices, is used. The values are summarised in Table A2.3.

Holland et al. (2005): Damages per tonne emission of $PM_{2.5}$, NH_3, SO_2, NO_X and VOCs from each EU25 Member State

The latest European update of damage costs for air emissions is found in Holland et al. (2005). The procedure is the same as in Figure 1. In relation to earlier calculations a new model has been used for modelling the dispersion of the emissions. By undertaking individual model runs for each EU country (i.e. by keeping other countries' emissions at a constant level and only changing the emissions for the given country) individual damage costs have been calculated on a national level. The Danish figures are summarised in Table A2.3. Valuation of a statistical life is based on updated figures from NewExt (2004) which amount to EUR 120,000 for average VOLY, and EUR 2,000,000 for average VSL, respectively. The valuation of damage includes the effects on mortality and morbidity as well as damage to agricultural crops. Effects on ecosystems and cultural assets are not included.

Unit price for methane emissions

Methane contributes to the greenhouse effect and thereby potential global warming. Damage from methane emissions is relevant for potential global damage from future climate changes. It is especially difficult to value these potential damages or in the first instance just to predict them. In this research note, the shadow price method has therefore been chosen for the calculations, i.e. the marginal costs associated with reducing CO_2 emissions in other places in Denmark. By implementing trading for CO_2 quotas in the EU in Spring 2005, EU's Emission Trading System (ETS), it is the actual quota price which gives the marginal reduction costs for Denmark. The argumentation behind this is simple: if the quota price in an international market is higher than the national reduction costs, then it pays to reduce CO_2 emissions in Denmark. If the quota price is lower that the national reduction costs, then it is more advantageous to buy quotas instead of making reductions in Denmark.

The price of CO_2 quotas was high in the start-up phase, averaging EUR 25 until May 2006, but has come down to a level of approximately EUR 15 since. As shadow price an average price of EUR 20 per tonne CO_2 has been selected here. Methane has a considerably higher global warming potential than CO_2. In UNFCCC (2003), a conversion factor of 21 for methane in relation to CO_2 emissions is recommended, i.e. 1 tonne CH_4 equates to 21 tonnes CO_2.

Table A2.3 Damage costs used in the analysis

	Holland et al. (2005)		Andersen et al. (2004) Zealand	West Jutland	Average quota price
Unit	EUR/tonne	EUR/tonne	DKK/kg	DKK/kg	EUR/tonne
Increased mortality valued via:	VOLY	VSL	VSL	VSL	
NO_X	6700	12100	86	79	
NMVOC	970	2000	na	na	
CO_2					20
CH_4					420

5 Damage costs for three different gas engines in Denmark

Table A2.4 summarises the damage costs introduced in the previous section, converted to DKK/g by using an exchange rate of 7.4 DKK/EUR. For the calculations in Table A2.5 the price per gramme VOC from Holland et al. (2005) (0.0148 DKK/g) is used, based on the average VSL value and the price per gramme NO_X from Andersen et al. (2004) (0.086 DKK/g), based on a coal-fired power station on Zealand. It is assessed that the Danish study provides a more accurate picture of damage costs from Danish emissions. As this study has not estimated a price for VOC it is necessary to take the VOC price from the European study. This unfortunately leads to an inconsistency with regard to the price used for VSL, as neither the median nor the average value for a VSL from Holland et al. (2005) agree with the VSL value used in Andersen et al. (2004). The price for CH_4 is calculated as the quota price for CO_2 times 21 to take into account methane's higher global warming potential.

Table A2.5 shows emission coefficients for two gas engines, Ulstein Bergen and Cat 3600, as well as an average Danish gas engine published in Nielsen and Illerup (2003). By multiplying the emission factors by the relevant damage costs from Table A2.4 the damage costs are provided in DKK per GJ, as shown in the last three columns in Table A2.5.

Table A2.4 Damage costs in DKK/g

	Holland et al. (2005)		Andersen et al. (2004)		Average quota price for CO_2
Increased mortality valued through:	VOLY (average)	VSL (average)	VSL		
Based on:	Average energy mix for Denmark		Zealand	West Jutland	
NO_X	0.0496	0.0895	0.0860	0.0790	
NMVOC	0.0072	0.0148	na	na	
CH_4					0.0031

Table A2.5 Emissions and damage costs for three different gas engines

	Emissions (g/GJ)			Damage costs (DKK/GJ)*		
	Natural gas engines	Ulstein Bergen	Cat 3600	Natural gas engines	Ulstein Bergen	Cat 3600
NO_X	168	232	91	14.45	19.95	7.83
NMVOC	117	156	147	1.73	2.31	2.18
CH_4	520	694	655	1.62	2.16	2.04
CO	175	225	145	na	na	na
Sum				17.80*	24.42	12.04

* Example calculation for natural gas engines:

The sum of damage costs (17.80) = 0.086 x emission factor NO_X (168) + 0.0148 x emission factor NMVOC (117) + 0.0031 x emission factor CH_4 (520).

Use of damage costs means in principle a simple weighting of emissions in relation to each other. By involving monetary values for damage it is possible to express 'damage potential' for all three engines in the same units, i.e. DKK/ GJ. Table A2.5 shows that emissions from the Ulstein Bergen are twice as 'damaging' as emissions from the Cat 3600. These damage costs can be seen in relation to production costs, differences in energy consumption and other effects which are involved in a valuation of different engine types.

It should be noted that the figures in Table A2.4 and Table A2.5 are provided without uncertainty intervals and thereby it is not possible to give an impression of uncertainty connected with calculation of the prices and, in turn, damage costs. That single values are provided is primarily due to that the sources mentioned earlier do not provide uncertainty intervals either, even though it must be assumed that each step from modelling of the emissions to valuation of the individual impact is associated with uncertainty. Therefore, if the above-mentioned figures are to be used for a prioritisation between different technologies, it would be important that sensitivity analysis is undertaken.

6 Conclusion

This research note has described the most important elements in estimating damage costs for air pollution emissions. This comprised explanation of the cause-effect chain between dispersion, exposure and the final physical effects, a review of valuation methods used to estimate monetary values for these effects as well as a short description of the two methods for calculating the value of a change in mortality, which often constitutes the largest part of the damage costs.

Damage costs for three different emissions, NO_x, VOC and CH_4 were taken from Danish and European publications, as well as the actual quota price for CO_2, and these were used to assess and compare damage costs per GJ for three different gas engines. This made it possible to weight the potential damaging impacts associated with the emissions. However, it is important to undertake sensitivity analysis, especially in the case where the difference between two engines not only means a reduction in all emissions, but possibly that the one emission increases while the other is reduced.

Generally it is important to note that large uncertainty is associated with estimating damage costs for air emissions, just as the three emission types here only comprise a fraction of the total emissions from the different engines. At the present time, no reliable damage costs for CO exist, just as other emissions, e.g. particulates, which are not included here can change the overall result.

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Annex 3: Conversion formula

The following conversion formula between mg/m^3_n and g/GJ (natural gas) has been applied:

$$EMF_{g/GJ} = \frac{EMF_{mg/m3} \cdot 0{,}237586}{21 - O_2}$$

where

$EMF_{mg/m3}$ is the emission factor in mg/m^3_n

O_2 is the oxygen percent to which the emission factor in mg/m^3_n refers

EMFg/GJ is the emission factor i g/GJ

The constant 0.237586 has been calculated by DGC based in the natural gas quality in 2002.

Annex 4: Revised full-load emission factors for Rolls Royce and Wärtsilä engines

The background data for the revised emission factors are the accredited measurement reports made available for the project by plant owners.

Table A4.1 Rolls Royce full-load emission factors

		Emission factor g/GJ	Average g/GJ	Distribution g/GJ	Min g/GJ	Max g/GJ	No of engines with measurements	No of measurements	Coverage
Rolls Royce	Electrical efficiency	41.7	41.7	0.6	40.3	44.5	53	53	65%
Rolls Royce	CO	68	65	32	21	266	53	53	65%
Rolls Royce	NO_X	156	157	8	126	166	53	53	65%
Rolls Royce	UHC	483	486	35	424	570	53	53	65%
B35:40	Electrical efficiency	44.6	44.6	0.1	44.5	44.7	2	2	-
B35:40	CO	19	22	12	13	30	2	2	-
B35:40	NO_X	158	157	5	154	160	2	2	-
B35:40	UHC	303	304	3	302	306	2	2	-

Table A4.2 Wärtsilä full-load emission factors

		Emission factor g/GJ	Average g/GJ	Distribution g/GJ	Min g/GJ	Max g/GJ	No of engines with measurements	No of measurements	Coverage
25SG	Electrical efficiency	39.9	40.2	0.8	38.4	41.8	19	20	82%
25SG	CO	65	71	19	50	110	19	22	82%
25SG	NO_X	127	140	19	96	171	19	22	82%
25SG	UHC	475	435	76	324	590	19	22	82%
34SG	Electrical efficiency	41.5	41.1	0.9	40.4	43.9	15	15	61%
34SG	CO	108	113	61	74	263	15	15	61%
34SG	NO_X	137	132	17	111	166	15	15	61%
34SG	UHC	402	436	81	243	557	15	15	61%

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