Environmental optimisation of natural gas fired engines

Main report
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RAPPORT

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1 Introduction

This is the final report of the PSO ForskEL project No. 010089 “Environmental optimisation of natural gas fired engines”. In addition to this report two supplementary reports and a note have been published.

- Report 1, “Environmental optimisation of natural gas fired engines. Measurement on four different engines. DGC 2010.
- Report 2, "Environmental optimisation of natural gas fired engines - calculation of health externalities" NERI 2010.
- Note 1. "Socio-economic analysis of environmental optimisation of natural gas fired engines", NERI 2010.

This report summarizes the already published reports and elaborates on the analysis of the importance of emission of different species from natural gas fired engines. Finally, different economic aspects are presented.

The participants in the project are:

- Rolls Royce, Danmark
- Wärtsilä, Danmark
- National Environmental Research Institute, DMU
- Danish Gas Technology Centre, DGC

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2 Summary

Adjustments leading to lower NO_x emissions normally lead to increased emissions of unburned hydrocarbons (UHC) and CO. This means that often engine adjustment is a trade-off between NO_x and other emissions. However, engines for CHP production are normally adjusted to meet the emission demands given by regulations and to obtain high efficiency. The engines meet the demands given by environmental regulations, but that does not mean that the engines are adjusted to obtain the lowest environmental impact. One reason is that, so far, it has not been possible to specify what is actually the lowest environmental impact. The cost of damages caused by NO_x emissions is given as DKK per kg NO_x emitted. Similar values are available for NMVOC (non-methane volatile organic compounds). But as the name indicates, NMVOC is a group of compounds, the composition of which depends on the source.
Therefore, the general cost of NMVOC cannot be used for determining the environmental and health related costs caused by emissions from natural gas fired engines.

The overall aim of the project has been to assess to which extent it is possible to reduce the emissions by adjusting the different engines examined and to determine the cost of the damage caused by emissions from natural gas combustion. However, only health and climate effects are included.

The emissions of NO_x, CO and UHC as well as the composition of the hydrocarbon emissions were measured for four different stationary lean-burn natural-gas fired engines installed at different combined heat and power (CHP) units in Denmark. The units were chosen to be representative of the natural gas fired engine-based power production in Denmark. The measurements showed that NO_x emissions were relatively more sensitive to engine setting than UHC, CO and formaldehyde emissions. By reducing the NO_x emissions to 40 % of the initial value (from 500 to 200 mg/m^3(n) at 5 % O_2) the UHC emission was increased by 10 % to 50 % of the initial value. The electrical efficiency was reduced by 0.5 to 1.0 percentage point.

Externalities in relation to power production are defined as the costs, which are not directly included in the price of the produced power. Health effects related to air pollution from power plants fall under this definition and usu-

ally dominate the results on external costs. For determination of these effects the exposure of the population, the impact of the exposure and the societal costs accompanying the impacts have been evaluated. As expected, it was found that when the engines are adjusted in order to reduce NO_x emissions, the emission of UHC increases and vice versa. It was found that at high NO_x emission levels (500 mg/m^3_n at 5 % O_2) the external costs related to the NO_x emissions are 15 to 25 times the costs related to UHC emissions. At low NO_x emission levels (200 mg/m^3_n at 5 % O_2) the costs related to NO_x are 5 to 8 times the costs related to UHC emissions.

Apparently, the harmfulness of formaldehyde (HCHO) and CO are negligible compared to UHC and NO_x emissions. It was found that the costs related to damage caused by NO_x are more than 10,000 times higher than the costs related to CO emissions and more than 100,000 times higher than the costs related to formaldehyde emissions at all examined cases.

Due to higher fuel consumption at low NOx conditions the balance price electricity where it becomes profitable to cover a heat demand by using engines instead of boilers might increase. That can lead to fewer hours of operation for engines.

From a welfare economic point of view the low NO_x operation conditions seem to be the best despite increased gas consumption and CO_2 and CH_4 emissions. The welfare economic value of the health effects more than compensates for the negative consequences.

3 Background

The Danish EPA has proposed that NO_x emission from gas engine plants is reduced in order to fulfil part of the Danish obligations in the NEC directive [1]. Today, engines are adjusted to meet the demands given by regulations and to obtain a high efficiency.
However, NO_x reducing engine adjustments affect properties such as CO and UHC emissions and electrical and heat efficiency.

The efficiency and emissions from lean-burn natural-gas fired engines are very dependent on parameters as

- Ignition timing
- Excess of air
- Charge air temperature
- Load
- Characteristics of possible auxiliary cleaning devices

The engines installed at CHP plants in Denmark are lean burn engines. The reason for operating the engines lean is to obtain high efficiency and low NO_x emissions. Increasing the excess of air leads to lower combustion temperature and thereby also lower NO_x emissions. A drawback of increasing the excess of air is a decreasing flame speed. Typically, lean-burn engines at CHP plants are operated with an excess of air around λ=1.9 - 2.2. If the excess of air is too high, the efficiency decreases due to lower flame speed and poorer combustion conditions leading to higher unburned fuel emissions.

The relation between the different emissions varies from engine type to engine type and for some engine types the UHC emissions are more sensitive to adjustments leading to lower NO_x than other engines.
Some correlations between emissions, efficiency and engine settings exist for early versions of lean-burn gas engines [2]. New versions of lean-burn engines, such as pre-chamber engines, have been introduced and now accounts for approx 50 % of the installed gas-engine based power capacity in Denmark. Also emission regulations have been changed and a number of engines are now fitted with supplementary emission reduction equipment.

The engines meet the demands given by regulations, but that does not mean that the engines are adjusted to obtain the lowest environmental impact. One reason is that, so far, it has not been possible to specify what is actually the lowest environmental impact. The cost of damages caused by NO_x emissions is given as DKK per kg NO_x emitted. Similar values are available for NMVOC (non-methane volatile organic compounds). But as the name indicates, NMVOC is a group of compounds, the composition of which depends on the source. For instance, the NMVOC composition of organic solvents from the paint industry differs significantly from NMVOC coming from emissions from natural gas fired engines. Measurements carried out by DGC [3] have shown that the latter has a composition more or less similar to that of natural gas. This is mainly C_2H_6 and C_3H_8, which are relatively harmless compared to organic solvents. Other compounds like formaldehyde are also present in emissions from natural gas fired engines, but there are practically no components such as benzene and PAH.

Therefore, the generally applied cost of NMVOC is not applicable for determining the environmental and health related costs caused by emissions from natural gas fired engines.

In the project the environmental cost of NMVOC emissions from natural gas fired engines will be determined and applied for calculation of the total cost of the environmental impact caused be emissions from natural gas fired engines for CHP production.

4 Measurements

4.1 Examined engines

Four different natural gas fired engines were chosen for measurement of emissions as well electrical and heat efficiency. The four engines are in operation on four different combined heat and power plants (CHP) in Denmark. Make and size of the engines are given in Table 1. They are all pre-chamber engines.

Table 1 Make and size of the examined engines

Unit	Make	Size
#1	Rolls Royce B35:40	4990 MW_e
#2	Rolls Royce KVGS-G4	2075 MW_e
#3	Wärtsilä V25SG	3140 kW_e
#4	Wärtsilä V34SG	6060 kW_e

The engines were selected to be representative for the natural-gas engine-based CHP production in Denmark. The engine at unit #1, the Rolls Royce B35:40, is a relatively new type of engine. The other three engines are commonly used at CHP units. The four examined engine types account for around 40 % of the total natural gas consumption on natural-gas engine-based CHP units in Denmark.

4.2 Operation conditions

For all four engines, emissions and efficiency were measured at different combinations of excess of air (λ) and ignition timing (IT). The excess of air and the ignition timing were set so that the following NO_x emission levels were obtained:

500, 400, 300, and 200 $mg/m^3(n)$, ref. 5 % O_2[1]

[1] Referring the emission limit to a certain O_2 concentration, eliminates the effect of diluting the flue gas with air by operating the engine lean. The corrected concentration is found as

$$C_{O2=5\%} = C_{measured} \frac{21\% - 5\%}{21\% - O_{2,measured}}$$

For each of the examined operational conditions the following measurements were conducted:

- O_2, CO_2, CO, NO_x, NO_2, UHC (by Flame Ionization Detector, FID)
- Hydrocarbon composition (by Fourier transform infrared spectroscopy (FTIR), including formaldehyde
- For each engine 2-3 samples were collected for Gas chromatograph (GC) analysis
- Natural gas consumption, heat and electricity production

The engine settings were chosen by the engine supplier. It was done to fit the scheme shown in Table 2. As shown in the table four measurements with fixed excess of air and fixed time of ignition and four measurements with fixed time of ignition and different excess of air are carried out. However, for one of the engines it was only possible to obtain steady operation at seven of the eight chosen engine settings.

Table 2 Examined operational conditions. IT denotes the time of ignition, M is numeration of individual measurements.

Unit: $mg/m^3(n)$ @ 5 % O_2	IT_1	IT_2	IT_3	IT_4
λ_1			M_5 NO_x = 200	
λ_2			M_6 NO_x = 300	
λ_3	M_1 NO_x = 200	M_2 NO_x = 300	$M_{3/7}$ NO_x = 400	M_4 NO_x = 500
λ_4			M_8 NO_x = 500	

Emissions and efficiencies for one of the examined engine are given in Figure 1.

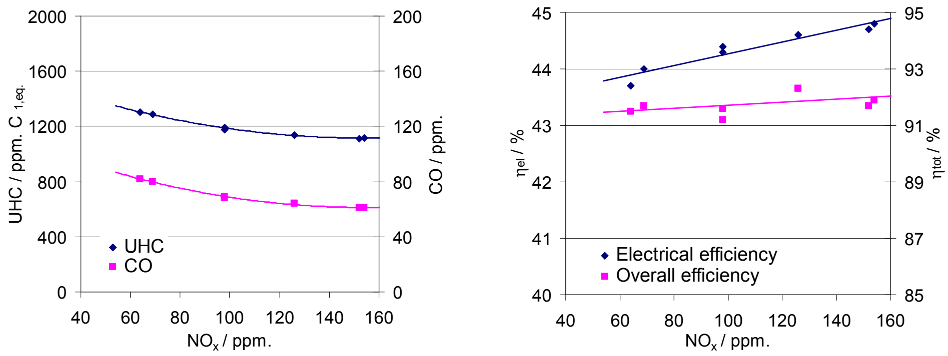

Figure 1 Emissions and efficiencies for the examined engine settings. Unit #1

The measurements are described in detail in [3].

5 Externalities

5.1 The EVA model system

The health cost externalities are calculated using the EVA model system (External Valuation of Air pollution, Andersen et al., 2004) developed at the National Environmental Research Institute (NERI) - Aarhus University along the lines of the impact pathway chain originating from the ExternE project [5]- [8], see Figure 2.

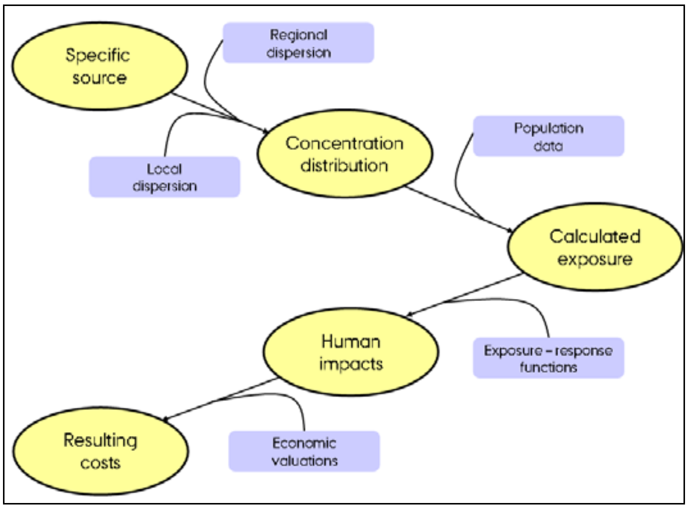

Figure 2 The ExternE impact - pathway approach for calculation of externalities from site-specific emissions of air pollutants. The regional dispersion in the EVA system is calculated with the DEHM model and the local dispersion is calculated with the OML-Multi model.

The system consists of a regional scale atmospheric chemistry transport model (the Danish Eulerian Hemispheric Model, DEHM) and a local scale atmospheric transport model (the Operational Meteorological Model, OML) which together are applied to calculate footprints of the components emitted from single sources as e.g. the CHP engines in the present project. The footprints correspond to marginal changes in annual concentrations of air pollutants, here called delta-concentrations, and they are calculated for the chemical components NO_2 (nitrogen dioxide), NO_3^- (nitrate), O_3 (ozone), CO (carbon monoxide), HCHO (formaldehyde), C_2H_4 (ethene) and C_3H_6 (propene). Based on the delta-concentrations and population data, the marginal population exposure is calculated. For the different chemical components a number of responses have been identified to the exposure, and the resulting health effects is calculated on derived exposure-response relations. Finally the associated costs in terms of direct and indirect costs for society are calculated.

In the present project the EVA system has been run for a number of scenarios corresponding to five investigation themes related to the range of measurements performed, and to the level of population exposure (ranging from low to medium and high exposure). The investigation themes are summarised in Table 3.

Table 3 Investigation themes of the present project.

Investigation theme	Details
A	Operation settings of engine unit #4 at medium exposure. In total six scenarios
B	High, medium and low exposure for the four engines in the reference setting. In total 12 scenarios
C	Operation settings of engine unit #1 at medium exposure. In total six scenarios
D	Operation settings of engine unit #2 at medium exposure. In total six scenarios
E	Operation settings of engine unit #3 at medium exposure. In total six scenarios

5.2 Health effects

The health effects applied in the present calculations consist of effects already included in the EVA system in previous studies and new effects included in the present study. The health effects of the original EVA system are listed in Table 4.

Table 4 Health effects included in the EVA system

Effect	Chemical component	Affected population
Acute mortality	SO_2, O_3	All
Respiratory hospital admissions	SO_2, $PM_{2.5}$, SO_4^{2-}, NO_3^-	All

Congestive heart failure	CO, $PM_{2.5}$, SO_4^{2-}, NO_3^-	> 65
Cerebrovascular hospital admissions	$PM_{2.5}$, SO_4^{2-}, NO_3^-	All
Chronic mortality	$PM_{2.5}$, SO_4^{2-}, NO_3^-, Dioxin	All
Bronchodilator use	$PM_{2.5}$, SO_4^{2-}, NO_3^-	Asthma
Cough	$PM_{2.5}$, SO_4^{2-}, NO_3^-	Asthma
Lower respiratory symptoms	$PM_{2.5}$, SO_4^{2-}, NO_3^-	Asthma
Chronic bronchitis	$PM_{2.5}$, SO_4^{2-}, NO_3^-	> 16
Restricted activity days	$PM_{2.5}$, SO_4^{2-}, NO_3^-	> 16
Lung cancer	$PM_{2.5}$, SO_4^{2-}, NO_3^-	> 16
Infant mortality	$PM_{2.5}$, SO_4^{2-}, NO_3^-	Babies
Loss of IQ-points	Pb, Hg	Babies and unborn

In the present project the following additional health effects have been included:

- Chronic mortality: formaldehyde (HCHO), ethene (C_2H_4) and propene (C_3H_6)
- Cough: nitrogen dioxide (NO_2)
- Asthma attacks (affecting asthma children): NO_2
- Lung cancer (affecting all): HCHO
- Cancer (affecting all): C_2H_4 and C_3H_6

Methane, ethane and propane are not considered carcinogenic and there is no mentioning in general literature of other chronic health effects. No health effects from these species will hence be included in the present study [4].

5.3 Results

5.3.1 Delta-concentrations, examples

The delta-concentrations give the marginal change in ambient concentration of a component which can be directly linked back to the emissions of the investigated source. In Figure 3 an example is given from one of the calculated scenarios in terms of delta-concentrations of different chemical components for engine unit #4 operated at engine setting 3/7 and located in an area with medium exposure.

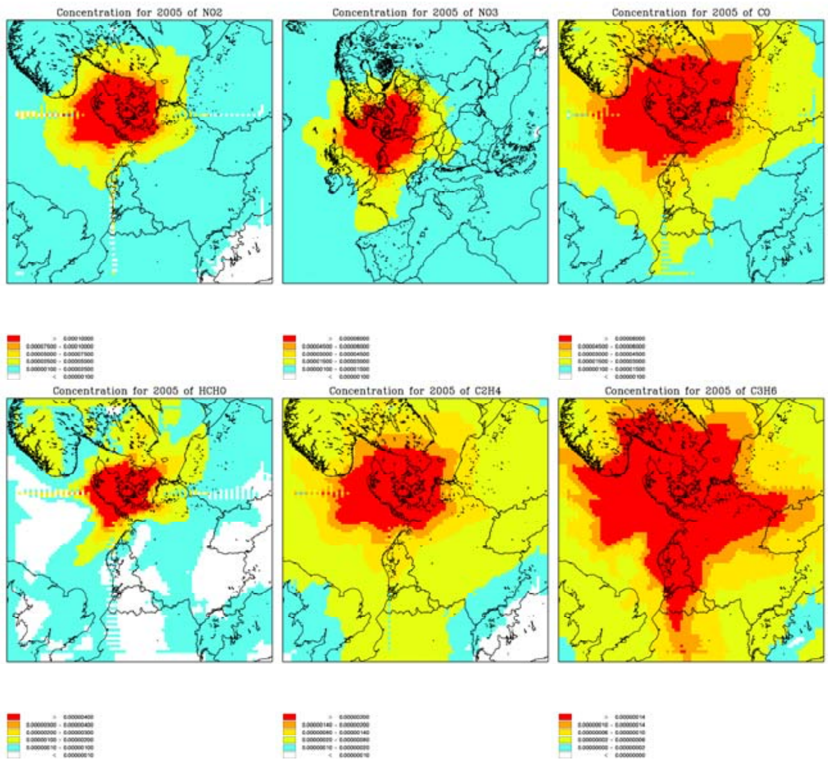

Figure 3 Delta-concentrations for engine unit #4 operated at engine setting 3/7 and located in a medium exposure area. Upper panel: NO_2 (left), NO_3^- (centre) and CO (right). Lower panel: HCHO (left), C_2H_4 (centre) and C_3H_6 (right).

For NO_3^- the whole European domain of the DEHM model is presented, since the delta-concentration of NO_3^- is more widespread than the other delta-concentrations. This is due partly to the fact the NO_3^- is not directly emitted, but instead formed in the atmosphere from the emitted nitrogen oxides and partly to the longer lifetime of NO_3^- compared to the other components.

5.3.2 Marginal health costs, investigation theme B

Table 5 presents the results from investigation theme B, which describes the variation in marginal costs with varying exposure for the reference operation settings (measurement 3/7) for all engines.

Table 5 Total costs (Euro) for four emitted components and unit cost (Euro pr kg) for nitrogen oxides (NO_x), carbon monoxide (CO), formaldehyde (HCHO) and ethene (C_2H_4).

Scenario	**Total (Euro)**	**NO_x (Euro/kg)**	**CO (Euro/kg)**	**HCHO (Euro/kg)**	**C_2H_4 (Euro/kg)**
Low exposure					
as_jl3_7	968151	16.7	6.5E-04	6.6E-04	0.17
as_ta3_7	714699	17.6	6.5E-04	6.9E-04	0.18
as_as3_7	377309	19.1	7.5E-04	10.2E-04	0.18
as_br3_7	530667	17.3	7.4E-04	8.6E-04	0.16
Medium exposure					
jl_jl3_7	1297693	23.9	8.7E-04	10.5E-04	0.29
jl_ta3_7	943192	23.5	8.8E-04	10.7E-04	0.3
jl_as3_7	496891	25.4	10.0E-04	17.0E-04	0.32
jl_br3_7	699222	24.6	9.6E-04	13.6E-04	0.28
High exposure					
sv_jl3_7	1283043	24.1	11.4E-04	14.0E-04	0.4
sv_ta3_7	931487	23.7	10.5E-04	7.7E-04	0.33
sv_as3_7	499139	25.9	12.7E-04	23.2E-04	0.44
sv_br3_7	697938	24.9	12.0E-04	17.3E-04	0.37

The EVA model system, the system setup in the present project and the determination of externalities are described in details in [4].

6 Operation on market conditions

From January 1st 2007 all CHP plants in Denmark with natural gas fired engines with an installed power larger than 5 MW_e sell the electricity at open-market terms (Nord Pool).

Decentralised natural-gas engine-based CHP plants must deliver the required heat for the grid or consumers connected. The amount of required heat varies significantly through the year. The heat can either be produced using an engine or a boiler. All decentralised CHP units are also equipped with boilers. By far the most common fuel for these boilers is natural gas. A few are, however, fuelled by other fuels as wood chips or wood pellets.

The operation and maintenance costs are significantly higher for gas engines than for boilers. Therefore, the required heat demand is covered by engines if the electricity price is sufficiently high and by boilers when the electricity price is low. When it becomes profitable to cover the heat demand by an engine, the electricity price is called the breakeven electricity price.

Where it is profitable to produce the required heat on an engine the breakeven electricity price varies significantly from plant to plant. Among other things it depends on:

Engine

- Price of natural gas (taxes are fixed)
- Service and maintenance costs
- Electricity and heat efficiency of the engine

Boiler

- Price of fuel
- Energy and CO_2 tax of fuel for the boiler if different from natural gas
- Boiler efficiency

7 Costs of electricity production at natural gas engines

When assessing the total costs related to production of electricity on natural gas engines a number of aspects should be taken into account. Among these are the fuel costs, value of products (heat and electricity) and the external costs related to negative environmental and health effects caused by harmful emissions from the plants.

The total costs related to the electricity production can be determined as

$$\text{Total costs} = \sum Cost_{External} + \sum Cost_{products} + \sum Cost_{production}$$

Where $\sum Cost_{External}$ is the cost of externalities caused by the harmful emissions in the flue gas from gas engines. It can be determined as

$$\sum Cost_{External} = m_{CH_4} \cdot C_{ext,CH_4} + m_{C_2H_4} \cdot C_{ext,C_2H_4} + m_{C_3H_6} \cdot C_{ex,C_3H_6} + m_{HCHO} \cdot C_{ext,HCHO} + m_{NO_x} \cdot C_{ext,NO_x} + m_{CO} \cdot C_{ext,CO} + m_{CO2} \cdot C_{ext,CO_2}$$

Production costs

- Natural gas
- Gas engine operation
- Gas boiler operation

Value of products

- Heat
- Electricity

For the individual engines included in this survey the electricity production is the same at all examined engine settings. Therefore, the income from electricity production is independent of the engine settings chosen.

Different engine settings result in different electrical and total efficiencies. As the electricity production is kept constant and the efficiencies vary, the natural gas consumption and heat production from the engine will change according to engine settings. As mentioned earlier, most plants are equipped with one or more natural gas boilers for heat production. It was seen from

the conducted measurements that when the electrical efficiency of the engine increases due to changed settings the heat production decreases.
In order to take this effect into account it is assumed that the difference in heat production will be covered by the natural gas boiler. In this way the heat production is kept constant and thereby the income from heat production is independent of chosen engine settings as well.

Additional natural gas consumption of the boiler can be determined as

$$V_{fuel,boiler,i} = \frac{Q_{ref} - Q_i}{H_L \eta_{boiler}}$$

where

Q_{ref} is the heat production for the measurement with highest heat production

Q_i is the heat production for each the conducted measurements

H_L is the lower heating value of the fuel

η_{boiler} is the marginal heat production efficiency for the boiler

As the boiler operation regarded here only is due to changes in heat efficiency of the engines due to changed engines settings, the natural gas consumption for the boiler is low compared to that of the engine. The conducted measurements showed that the gas consumption of the boiler would be maximum 2 % of the gas consumption of the engine. Furthermore, the emissions from the boiler are low compared to emissions from the engines. Therefore, the cost of externalities from the boiler can be neglected in this analysis.

With this approach the effect of varying electricity prices and different heat prices at different locations are eliminated, see Figure 4 and Figure 5. The only parameter - beside emissions - that is affected by changing engine settings is the natural gas consumption.

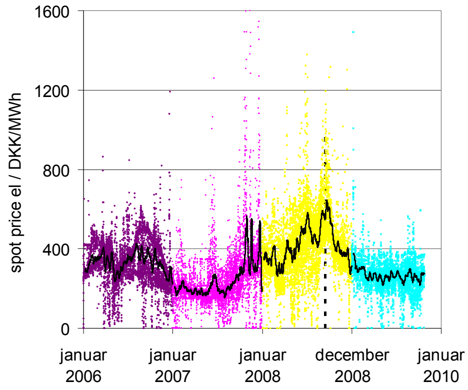

Figure 4 Nord pool electricity prices 2007-2009 [19]

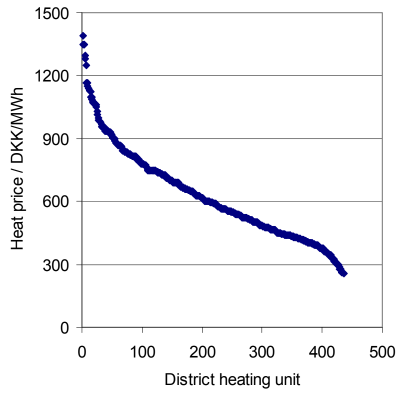

Figure 5 Consumer heat prices for different district heating unit. 2009 [20]

7.1 Influence of engine settings

From the measured emissions and the specific costs of externalities related to the emissions it possible to determine the effect of changing engine settings on externalities related to the emissions.
Figure 6 to Figure 9 show the cost of externalities for the related production of 1 MWh of electricity for the different emissions for the four examined engines. Despite the fact that the CHP units produce both electricity and heat all externality costs are put on electricity production using this presentation of the results. The value of changes in climate gas emissions is based on the expected price of tradable CO_2 permits of about 125 kr. per ton [10].

The figures show that at the higher NO_x levels, NO_x emissions by far cause the highest externality costs. Even at low NO_x emissions - 200 mg/m^3 - the NO_x emissions result in higher externality costs than all other species together. At all conditions, the second most costly component is CO_2.

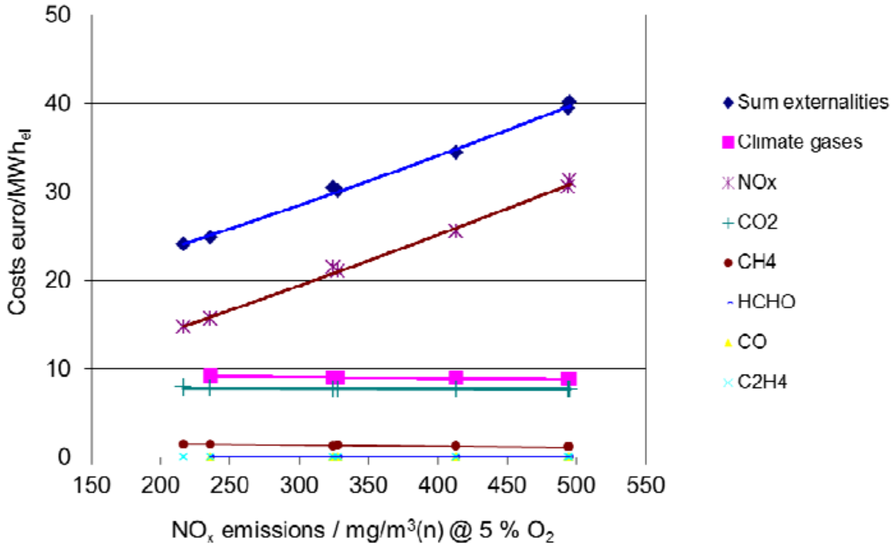

Figure 6 Specific cost of externalities for engine unit #1. Medium exposure level.

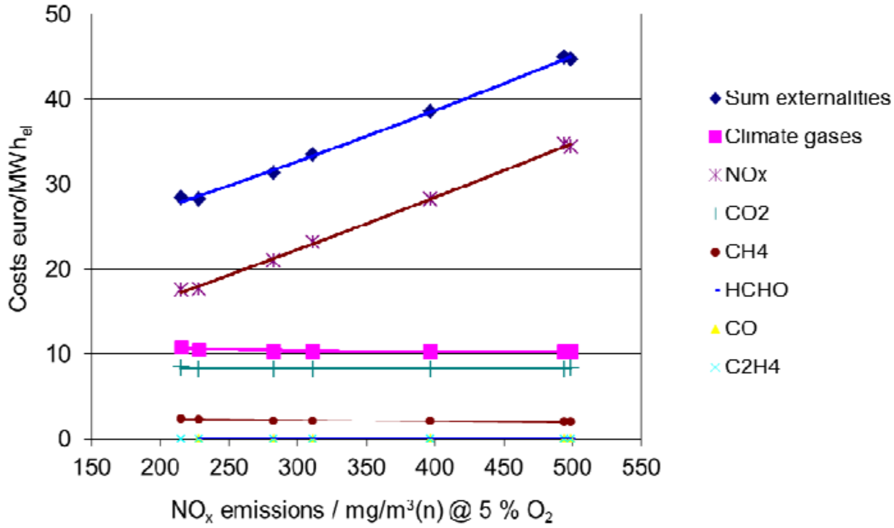

Figure 7 Specific cost of externalities for engine unit #2. Medium exposure level.

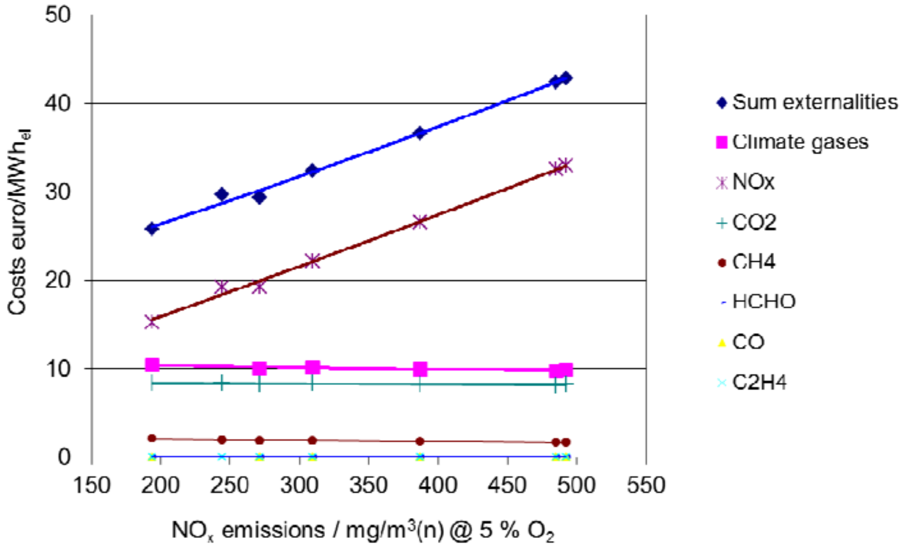

Figure 8 Specific cost of externalities for engine unit #3. Medium exposure level.

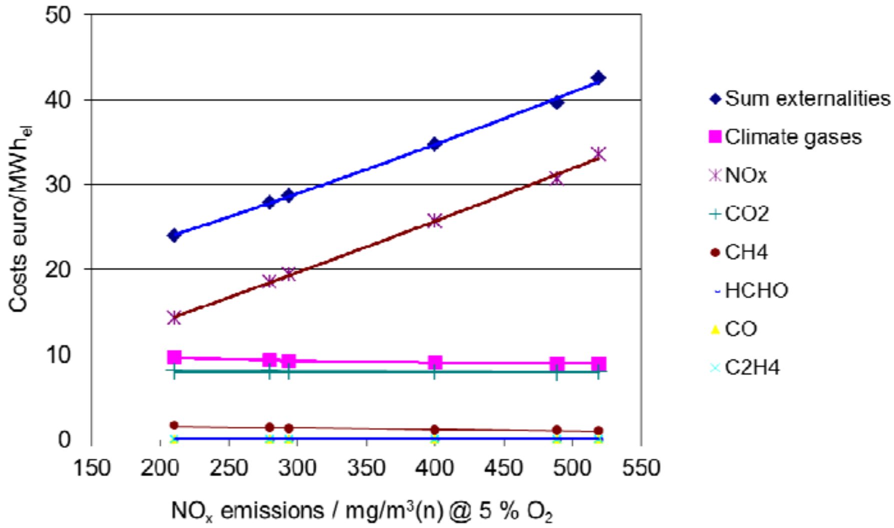

Figure 9 Specific cost of externalities for engine unit #4. Medium exposure level.

As previously mentioned there is a trade-off between NO_x emissions and UHC emissions. If the engine is adjusted in order to reduce NO_x emissions, the emission of UHC increases and vice versa. The figure shows that at high NO_x emission level - 500 mg/m^3_n @ 5 % O_2 - the costs related to NO_x are 15 to 25 times higher than the costs related to UHC emissions. At low NO_x

emission level - 200 mg/m^3_n @ 5 % O_2 - the costs related to NO_x emissions are 5 to 8 times higher than the costs related to UHC emissions.

Apparently, the harmfulness of formaldehyde (HCHO) and CO is negligible compared to UHC and NO_x emissions. To illustrate that this is the case the specific cost of externalities for engine unit #1 is shown in Figure 10 on a logarithmic scale. It is shown that the costs related to damages caused by NO_x are more than 10,000 times higher than the costs related to CO emissions and more than 100,000 times than the costs related to formaldehyde emissions at all examined cases.

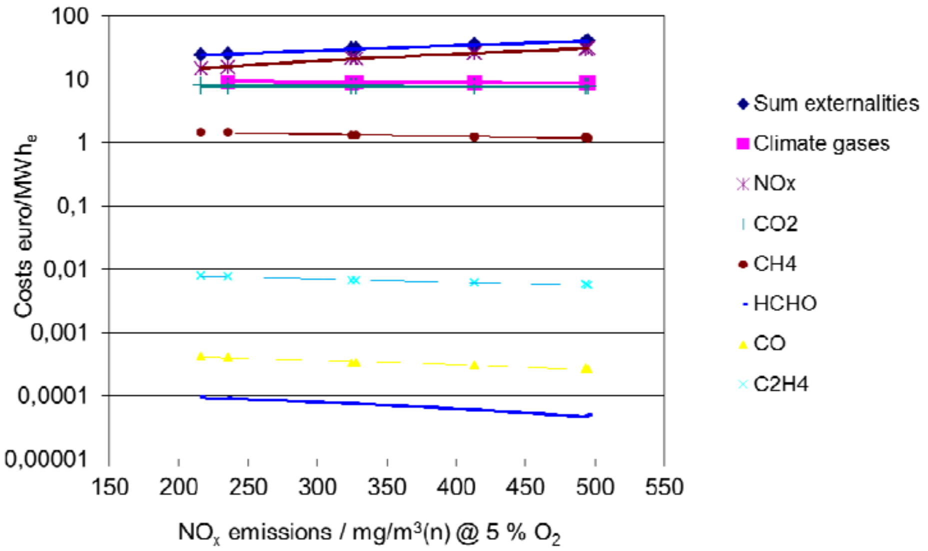

Figure 10 Specific cost of externalities for engine unit #1. Medium exposure level. Same as Figure 6 but depicted on a logarithmic scale.

Reducing NO_x emissions by increasing excess of air or retarding ignition leads to lower efficiency and thereby to higher natural gas consumption in order to maintain the same electricity production.

The costs related to emissions that are described above are the socio-economic costs and not the costs paid by the power plants. Therefore, the natural gas price that should be compared with the externality related costs is the socio-economic value of natural gas and not the market price. The socio-economic value of natural gas is assumed to be the value estimated by the Danish Energy Agency (see Figure 15) multiplied by 1.17, which is a standard conversion factor that should be applied for socio-economic analysis [22].

In Figure 11 the sum of the included externalities, the socio-economic value of natural gas and the sum of the two are shown for the four examined engines. The costs related to externalities represent between one third and two thirds of the socio-economic value of the natural gas. It is seen that the sum of the included externalities and the socio-economic value of natural gas decreases steadily for decreasing NO_x emissions.

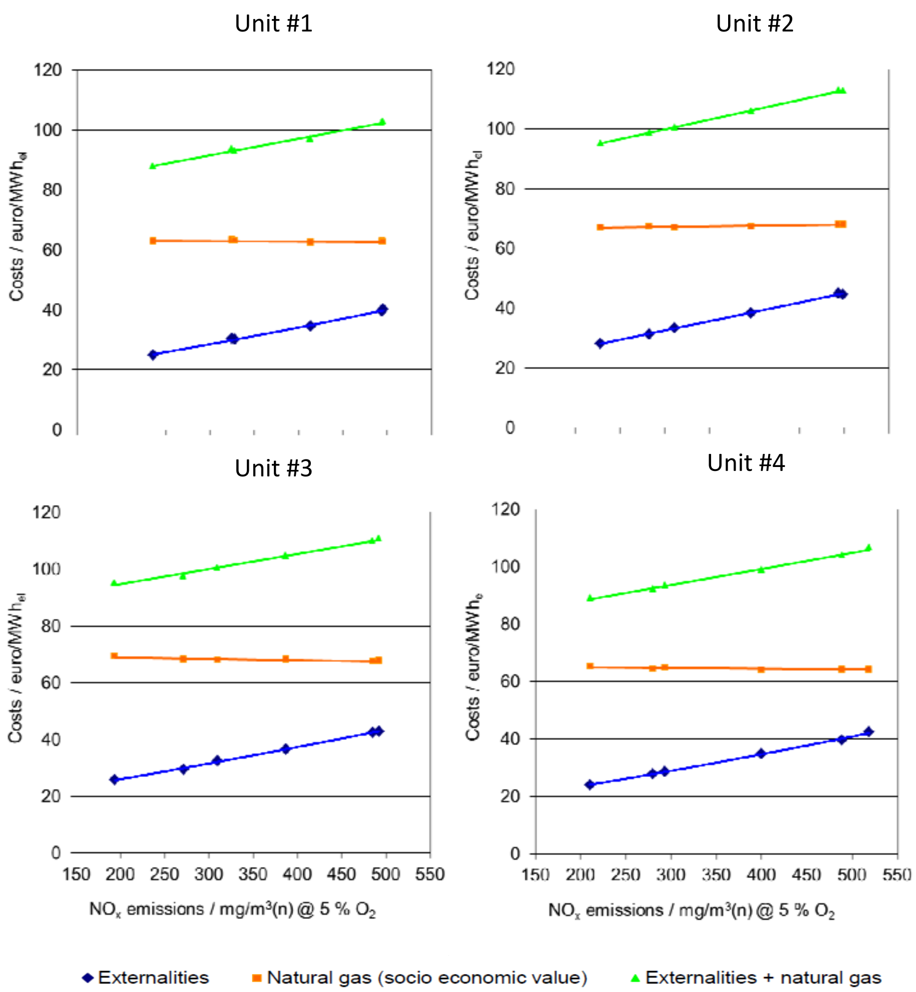

Figure 11 Specific cost of externalities, the socio-economic value of natural gas and the sum of the four examined engines. Medium exposure level.

7.2 Influence of location of plants

As previously described harmfulness of i.e. NO_x emissions depends on the number of persons exposed and, consequently, where i.e. NO_x is emitted.

The analyses described above are all based on medium exposure level. In order to assess the influence of location of the plant, model calculations were conducted for one set of engine settings for all four engines. The only parameter that was varied in the model was the location of the emission. Aså was chosen as low exposure location, Jelling was chosen as medium exposure location and St. Valby was chosen as high exposure location, see Figure 12.

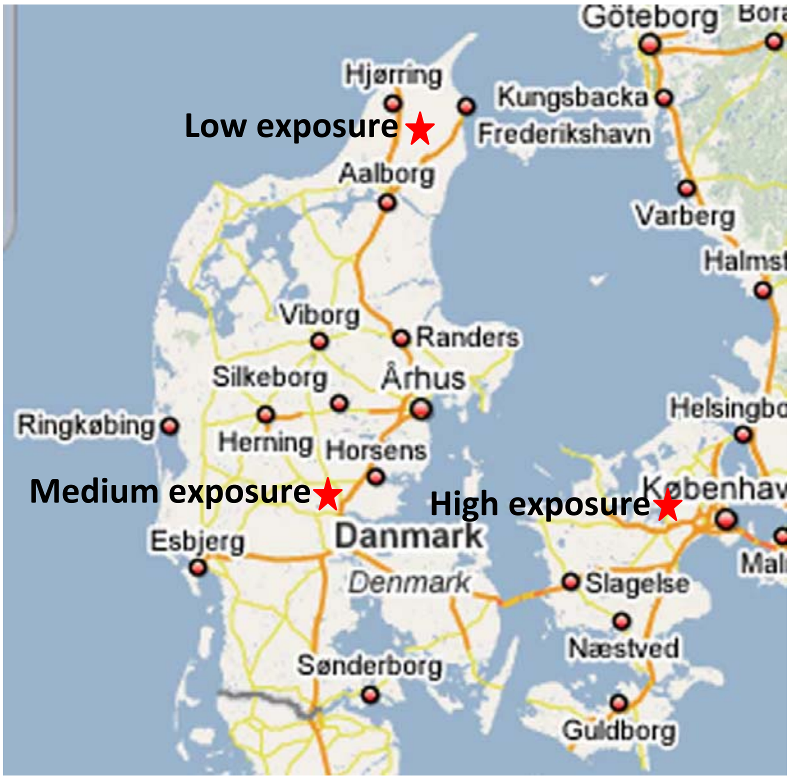

Figure 12 Low, medium and high exposure location

The calculations show that the externalities related to emission of CO_2 and CH_4 are independent of the location of the source of the emissions. That is because these gases only act as climate gases and therefore the effect is global. For NO_x emissions it is found that externality costs are 30-40 % higher for NO_x emitted in Jelling (medium exposure level) compared to the same emission emitted in Aså (low exposure level). If the same engine unit was located in St.Valby instead the externality costs would only increase by 1-2 % further despite the fact that it is expected to be a high exposure location. This is quite surprising.

The reason for choosing St. Valby as high exposure location is that it has been applied as such in previous studies. However, in these studies the emission source was a large power plant with much higher flow of flue gas and a 150 m high chimney. Small units as dealt with in this study have a low flow of flue gas and chimney heights from 25 to 32 m.
This means that the emitted NO_x will not be transported as far for small plants compared to emissions from large plants. It is believed that the explanation is that the unit should have been located closer to Copenhagen in order to be a true high exposure location.

Figure 13 Specific cost of externalities for the four examined engine units located at three different locations leading to different exposure levels. Engine setting 3/7 for all cases.

8 Budget and welfare economic assessments

The investigation reported above mainly deals with technical issues regarding emissions at different engine settings. Changed engine settings lead to derived economic implications. For instance, the natural gas consumption is affected by changing the operation conditions of the engines. The following sections will treat some of the related implications.

8.1 Fuel price

The price of natural gas is an important factor for the CHP units. CHP units buy gas in different ways. Some plants buy the gas on long-term contracts and others on short-term contracts. In recent years, the natural gas price has varied dramatically, see Figure 14. In September 2010, DONG Energy's list price was 2.98 DKK/m^3 and NGF Gazelle's was 2.85 DKK/m^3. These prices are exclusive taxes.

Figure 14 Official price for business customers exclusive VAT and taxes. From NGFGazelle [9].

The Danish Energy Agency foresees significantly lower natural gas prices compared to actual prices given by DONG Energy and NGFGazelle, see Figure 15.

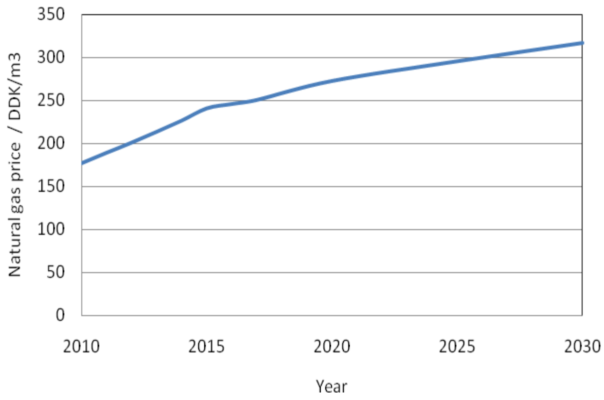

Figure 15 Natural gas prices foreseen by the Danish Energy Agency [10]

8.2 Taxation

8.2.1 Energy tax

For heat produced on natural gas fired boilers energy tax must be paid for the total amount of natural gas used. However, for heat produced on gas engines it is only the part of the fuel that is related to the heat production. The fuel used for electricity production is exempted from energy tax.
The fraction of fuel subject to energy taxation can be calculated by either the

V-formula: $$\frac{\eta_{heat}}{1{,}25}$$

or the

E-formula: $$1-\frac{\eta_{el}}{0{,}65}$$

η_{heat} and η_{el} are heat efficiency and the electrical efficiency, respectively.

The fraction of fuel subject to energy taxation is the lower of the two. Whether that is the V or the E formula depends on the electrical and the heat efficiency as shown in Figure 16. The line shows the combination of heat and electrical efficiency, where the E and the V formula give the same result. For units that can be plotted above the line it is the E formula that is applied and, correspondingly, for units below the line it is the V-formula. For the four examined engines all conducted measurements of heat and electrical efficiencies are given in the figure. It shows that in all cases the E formula should be applied.

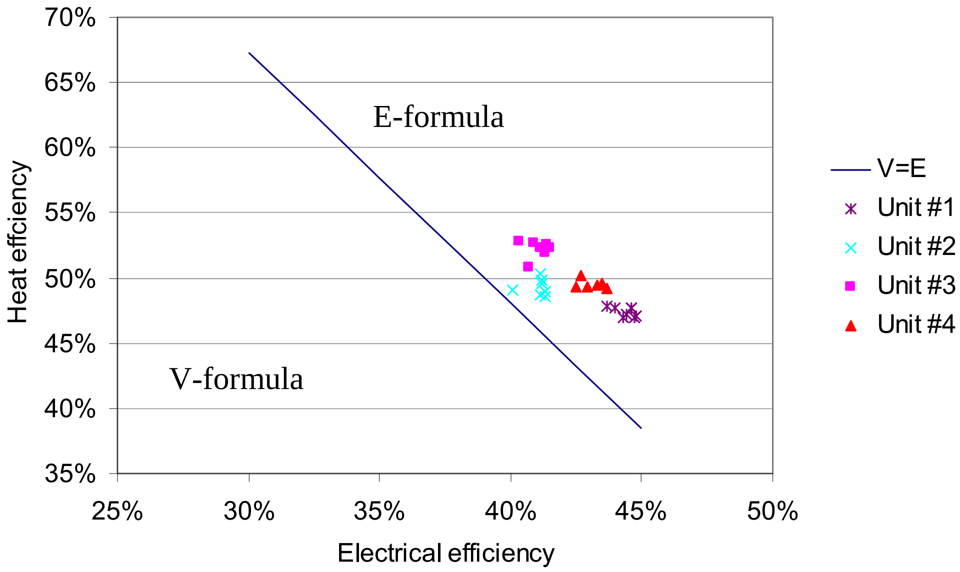

Figure 16 Energy taxation model

8.2.2 Tax on emissions

A CO_2 tax must be paid according to the amount of CO_2 emitted. For natural gas the CO_2 tax corresponds to 0,351 DKK/m^3 of natural gas [15]. This is around 150 DKK/ton of CO_2 emitted.

From 2010, a tax on NO_x emissions has been introduced and from 2011 a tax on methane emissions will be introduced. The tax on NO_x emissions is 5 DKK/kg and the tax for methane emission will correspond to the green-house gas potential. For natural gas fired engines the NO_x and the methane tax will correspond to 0.028 [17], [18] and 0.066 [19] DKK/m^3 of natural gas, respectively. For a natural gas boiler the NO_x and the methane tax will be 4 times and 100 times lower than for an engine.

8.3 Emissions and O&M costs

The present regulations on NO_x emissions from natural gas fired CHP engines is 550 mg/m^3(n) @ 5% O_2. In order to meet this demand the engines are running lean-burn conditions (high excess of air). If NO_x emissions should be reduced further to e.g. 200 mg/m^3(n) without post-treatment equipment it would require even leaner combustion conditions.

Leaning the combustion conditions further will require higher load on the spark plugs resulting in a shorter life time. Furthermore, very lean conditions will to some extent lead to poorer combustion conditions and possibly more unplanned stoppage of engines.

Later ignition as well as leaner combustion conditions will lead to lower combustion temperature and thereby lower NO_x formation, as mentioned earlier. Lowering the in-cylinder maximum temperature will also lead to lower maximum pressure and the lower maximum pressure will lead to lower service and maintenance costs.

It is assessed by the engine suppliers in the project that the above mentioned issues are of minor importance and that the higher spark plug costs balance the lower maintenance costs. Therefore, the change in operation and maintenance costs due to changed operation conditions can be neglected.

8.4 Calculation of breakeven price for electricity production

As mentioned earlier all natural-gas fired engine-based decentralised CHP plants in Denmark are obligated to provide heat to cover the local demand. Besides engines, the plants also have boilers installed for heat production only. The main part of these plants sells the produced electricity at market conditions. When the market price of electricity is below a certain level the heat demand is covered by heat from the boilers and when the electricity price is sufficiently high the heat demand is covered by heat from the engines producing electricity. Where it becomes profitable for the plants to operate the engines, the required electricity price is called the *breakeven* price.

Engine adjustments in order to reduce emissions might affect the breakeven price and thereby the number of operation hours. The breakeven price depends on a number of parameters which will be described below.

Base data and assumptions for calculation of breakeven price:

Fuel		
Natural gas price (without tax) [10], [11]	2,5	DKK/m^3
Energy tax (natural gas) [15], [16]	2,27	DKK/m^3
CO_2 tax (Natural gas) [15]	0,351	DKK/m^3
Gas engine		
Service & maintenance [12]	67	DKK/MWh el
Electrical efficiency	41	%
Heat efficiency	52	%
Subsidy electricity production [14]	80	DKK/MWh el

Tax on fuel to be used for heating is calculated according to the E-formula.

Boiler		
Service & maintenance [12]	5	DKK/MWh heat
Efficiency	100[2]	%

Biomass fired boilers are neglected here, since there is only a few of them.

With these conditions it is possible to calculate the price of producing heat at the gas engine to 625 DKK/MWh heat including taxes and subsidy for electricity production. However, income related to sale of electricity production is not included. The same amount of heat can be produced at a natural gas boiler for 446 DKK/MWh heat.

The breakeven price for electricity production is the price where the cost of heat production from a boiler equals the costs of heat production from an engine minus the income from the related electricity production.

$$Cost\ of\ heat_{engine} - income\ from\ electricty = Cost\ of\ heat_{boiler}$$

$$income\ from\ electricty = Cost\ of\ heat_{engine} - Cost\ of\ heat_{boiler}$$

The required price for electricity in order to make it profitable to produce heat at the engine can be determined as

$$Breakeven\ price_{el} = \left(price\ of\ heat_{engine} - price\ of\ heat_{boiler}\right)$$
$$= \left(625\ DDK / MWh - 446\ DDK / MWh\right) = 179\ DKK / MWh_{heat}$$

2 For condensing boilers it is possible to obtain efficiencies higher than 100 % relative to the lower heating value.

or related to electricity production

$$Breakeven\ price_{el} = 179\ DKK / MWh_{heat} \frac{\eta_{heat}}{\eta_{el}}$$

$$= 179\ DKK / MWh_{heat} \frac{52\%}{41\%} = 286\ DKK / MWh_{el}$$

This price varies significantly from plant to plant, depending on fuel prices and boiler and engine efficiencies.

8.4.1 Influence of engine settings on the breakeven price

From the obtained efficiency measurements the breakeven price was calculated for a low NO_x case and a high NO_x case for each of the four examined engines. It is assumed that all conditions are as given above. However, measured efficiencies for the four engines were applied instead what is stated above. This means that the only parameters included are efficiencies and, therefore, values given in Table 6 only show the effect of efficiency changes due to changed engine settings in order to obtain lower NO_x emissions. The numbers do not give the true breakeven electricity prices for the different plants.

As seen from Table 6 different engine settings leading to different emission levels will to a minor extent affect the breakeven price. The same tendency is found if the natural gas price given by the Danish Energy Agency is applied, see Table 7. It is seen that the breakeven price increases if the engine is optimised for low NO_x emissions. This might lead to fewer hours of engine operation and thereby less electricity production. The effect of this is not examined in this work. Furthermore, the analysis shows that the effect of changed engine settings on the breakeven electricity price apparently is different for each of the examined engines. For one engine it is of practically no importance and for another engine unit the breakeven price increases by 7 % when NO_x emissions are reduced from around 500 to around 200 mg/m^3(n). For the latter the measured overall efficiency is around 2 % higher for the 500 mg/m^3 case than for the 200 mg/m^3 case. That does not appear reasonable. An explanation could be that an erroneous heat measurement. If the change in overall efficiency is 1 % instead of 2 %, the breakeven price increases by 2 % instead of 7 %. This shows that the calculated breakeven price is very dependent on efficiencies.

Table 6 Influence of heat and electrical efficiency at low and high NO_x emissions on breakeven price of electricity production. Gas price: 2.50 DKK/m^3

NO_x level	≈200 mg/m^3(n)	≈500 mg/m^3(n)	Difference
Unit	DKK/MWh$_{el}$	DKK/MWh$_{el}$	DKK/MWh$_{el}$
#1 (measurement 1/4)	255,6	250,0	5,6
#2 (measurement 5/4)	269,2	268,9	0,2
#3 (measurement 1/4)	246,1	229,5	16,6
#4 (measurement 5/4)	247,5	239,7	7,9

Table 7 Influence of heat and electrical efficiency at low and high NO_x emissions on breakeven price of electricity production. Gas price: 1.76 DKK/m^3.

NO_x level	≈200 mg/m^3(n)	≈500 mg/m^3(n)	Difference
	DKK/MWh$_{el}$	DKK/MWh$_{el}$	DKK/MWh$_{el}$
#1 (measurement 1/4)	175,3	170,8	4,6
#2 (measurement 5/4)	186,1	186,1	0,0
#3 (measurement 1/4)	166,1	152,1	14,0
#4 (measurement 5/4)	168,0	161,5	6,5

Based on efficiencies measured for engine unit #4, the sensitivity of different parameters was assessed. The single most important parameter for breakeven electricity price is the fuel price. See Table 8.

Table 8 Sensitivity analysis on breakeven price for electricity production. Emissions as for Unit #4. Gas price 2.50 DKK/m^3.

NO_x level (mg/m^3(n))		≈200	≈500	Difference
		DKK/MWh$_{el}$	DKK/MWh$_{el}$	DKK/MWh$_{el}$
Reference		247,5	239,7	7,9
Gas price (taxes not changed) (Gas engine and boiler)	+ 10 %	304,0	295,2	8,8
Engine Service & maintenance	+ 10 %	261,7	253,9	7,9
Efficiency, boiler	+ 5 %	261,6	253,4	8,2
Boiler Service & maintenance	+ 10 %	247,0	239,1	7,8

8.5 Welfare economic effects

One thing is how the economy of the CHP plants and the breakeven price of electricity is affected by the changed operation conditions another is how society's welfare is affected by this. A welfare economic cost benefit analysis (CBA) is a statement of how changed operation conditions affect society's welfare. It takes not only welfare effects of changes in production and resource use into account but also welfare effects connected with environmental impact changes. In this project it primarily means the welfare economic value of emission changes. The effects of emissions are valuated and added to the resource costs. Any consequences for the public sector's net-revenue because of changed tax payments also have welfare economic consequences related to the so-called "dead weight loss" of tax payments.

In this section the results of a welfare economic analysis of the consequences of reducing NOx emissions by changing motor operation are presented. The analysis is based on the results from other parts of the project described in the preceding chapters and sections of this report and the analysis is more thoroughly documented in [23]. The welfare economic relevant consequences of reducing NO_x emissions is described in section 8.5.1 and in section 8.5.2 the results of valuating the consequences are presented.

8.5.1 Welfare economic consequences

As described earlier the engines are running with different combinations of ignition timing and excess of air – these are set in order to obtain NO_x emission levels of 500, 400, 300 and 200 mg/m^3. In the following the case with the highest NO_x level for engine unit #3 is used as reference as this makes it easier to see how welfare economic costs change when NO_x emissions decrease. In the accomplished experiments the engine effect was kept approximately constant, but this means that the production of heat will change with the changed operation conditions. Therefore in the welfare economic analysis it is assumed that the highest heat production should be maintained. This means that if changes in operation conditions lead to a decrease in heat production on engines this decrease is assumed to be substituted by production on gas boilers.

First of all these assumptions mean that consumption of gas will change with changes in operation conditions. Gas consumption on engines changes to maintain electricity production and to maintain heat production more gas are consumed on boilers. Secondly changes in heat production on boilers affect the maintenance costs of these. Thirdly emissions from CHP plants will change both because of changed operation conditions and gas consumption on engines and because of increases in gas consumption on boilers. Finally the consequences for gas consumption and emissions will affect tax payment which will have consequences for the size of the so-called dead weight loss of taxes.

All these consequences should be included in the welfare economic analysis and they are therefore summarized in Table 9.

Table 9 Consequences of changing the operation conditions of gas engine unit #3. Reference case is M4. Electricity and heat production are kept constant with 2000 hours of engine operation per year.

	M8 NOx = 500	M3/7 NOx = 400	M6 NOx = 300	M2 NOx = 300	M5 NOx = 200	M1 NOx = 200
Gas consumption – m^3	568	1,420	2,469	-1,262	10,148	2,596
Maintenance costs – kr.	52	- 20	- 3	- 384	165	- 488
Emissions – kg						
- NO_x	50	- 1,783	- 3,818	- 3,100	- 5,161	- 4,215
- CO_2	- 1,182	- 4,488	- 1,156	6,305	28,634	60,015
- CO	188	331	929	1,043	2,962	1,625
- CH_4	- 43	- 94	2,700	2,602	7,266	4,401
- HCHO [1]	29	65	115	166	338	288
- C_2H_4 [1]	7	22	79	101	209	158
Taxes – kr.	2,789	4,094	7,968	- 3,003	27,322	6,959

Source: Brodersen & Møller (2010)

Note: 1. Includes only emissions from engines

It is seen that in all cases except M2 (ignition time set so NO_x emissions are reduced to 300 mg/m^3) total gas consumption will increase as a consequence of reducing NO_x emissions relative to the situation under condition M4. Maintenance costs depend on the use of boilers as the maintenance costs of engines are unaffected by the changed operation conditions. The emissions to air change as a consequence of changed operation conditions and this is further discussed in sections 4 and 7. Tax payments include emission taxes as well as energy tax on gas consumption. The assumed tax rates and the assumed distribution formula are described in section 8.1 and in [23]. It is seen that tax payments are higher in all situations except M2. This is due to the higher level of gas consumption in these situations compared to situation M4. Generally, the yield from NO_x tax will decrease, but not to the same degree as the yield from energy and the other emission taxes increase.

8.5.2 Welfare economic costs

Based on the consequences of different operation conditions summarized in Table 1 welfare economic costs for each situation M1 to M8 compared to situation M4 can be calculated. This is done by use of so-called welfare economic accounting prices. This is further explained in [23].

The accounting price for gas is equal to the expected international gas price increased by a net tax factor of 1.17 [24]. The expected gas price of 1.63 DKK. per m^3[3] is stated in [10].

The welfare economic value of the maintenance costs are calculated as the amount in factor prices from Table 1 increased with the net tax factor 1.17.

The value of emission changes is estimated on the basis of the value of their health effects and their contribution to fulfilment of the Danish objective for reduction of climate gas emissions. The estimation and valuation of the health effects are further described in section 5 in this report as well as in [25] and [26]. The value of changes in climate gas emissions is based on the expected price of tradable CO_2 permits of about 125 kr. per ton [10].

Finally changes in tax yields have welfare economic value because they affect the need for changing other taxes. E.g. a decrease in tax yield requires that other taxes are increased to maintain the actual level of public expenditure. Such an increase gives rise to a so-called dead weight loss which is a welfare economic loss to society. The opposite will be the case if tax yield is increased which is the actual case where gas consumption and thereby also the yield from energy taxes increase in al situations except M2. This increase represents a welfare economic benefit because other tax rates can be reduced which means a decrease in dead weight loss.

[3] Gas transmission is not included.

Table 10 Welfare economic costs of changing the operation conditions of gas engine unit #3. Reference case is M4. Electricity and heat production are kept constant with 2000 hours of engine operation per year.

Unit: DKK.	M8 NOx = 500	M3/7 NOx = 400	M6 NOx = 300	M2 NOx = 300	M5 NOx = 200	M1 NOx = 200
Gas consumption	1,074	2,648	4,672	- 2,389	19,203	4,913
Maintenance costs	61	- 24	- 3	- 450	193	- 571
Emissions – health effects [1]	- 9,697	- 37,016	- 84,334	- 61,509	- 102,050	- 71,817
Emissions – CO_2 and CH_4 [2]	- 260	- 807	6,943	7,619	22,654	19,055
Deadweight loss	- 3,347	- 4,912	- 9,562	3,604	- 32,787	- 8,351
Welfare economic costs	- 12,169	- 40,111	- 82,284	- 53,125	- 92,787	- 56,771

Note: 1. Value of health effects in Denmark as a consequence of changed emissions from engines. It has not been possible to valuate the health effects of changed emissions from boilers.
2. Value of changed CO_2 and CH_4 emissions from engines as well as boilers.

The results of these welfare economic calculations are summarized in Table 10. It is seen that from a total welfare economic viewpoint all changes in operation conditions carried out to reduce NO_x emissions are better than M4. True, decreased NO_x emissions generally also mean increased gas consumption and this together with increased CO_2 and CH_4 emissions represent a welfare economic cost. However, increased gas consumption also gives rise to increased energy tax payments which is a gain to society. And most important In all situations the positive health effects represent an even larger gain to society.

From a welfare economic point of view the operation condition M5 seems to be the best even if it leads to the highest increase in gas consumption and CO_2 and CH_4 emissions. The welfare economic value of the health effects and reduced dead weight loss are so high that it more than compensates for the increase in gas consumption.

Operation condition M2 represents a special case because it leads to less gas expenditures as well as less tax payments. Therefore, from a budget economic point of view it will be preferred. Obviously there is a lack of accordance between what is welfare economically preferable and what is budget economically preferable. This represents a regulation problem which shall not be discussed here.

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