Environmental optimisation of gas fired engines

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1. ABSTRACT

Adjustments of natural gas fired engines leading to lower NO_x emissions normally lead to increased emissions of unburned hydrocarbons (UHC) and CO. This means that engine adjustment often is a trade-off between NO_x and other emissions. However, engines for combined heat and power (CHP) production are normally adjusted to meet the demands given by regulations and to obtain high efficiency. 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 harm caused by NO_x emissions is given as € 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 is not suitable for determining the environmental impact caused by emissions from natural gas fired engines.

The overall aim of the project was 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 harm caused by emissions from natural gas combustion. However, only health and climate effects are included. External costs of the following chemical components present in flue from natural gas fired engines are determined: NO_x (nitrogen oxides), C_2H_4 (ethene) C_3H_6 (propene) and HCHO (formaldehyde). Methane, ethane and propane are not considered carcinogenic, and there is no mentioning in general literature of other chronic health effects.

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 CHP units in Denmark. On average, the NO_x reduction potential corresponds to a reduction of 40 % relative to the present level. Such a NO_x reduction will lead to an increase of unburned hydrocarbon emissions of 12 % and the CO emission will increase by 19 %. Furthermore, the natural gas consumption for the gas engines will increase by 1.5 % in order to keep the power production constant. This is due to reduced electrical efficiency as a consequence of the NO_x reduction. However, increased natural gas consumption leads to increased heat production. This is taken into account by assuming that the heat production from the boilers is reduced accordingly.

The external costs related to emission will be decreased by 9 million € per year as consequence of a NO_x reduction as described above. A welfare economic analysis was conducted. Besides the external costs, costs related to fuel consumption, operation as well tax yield are included in the analysis. The analysis shows a potential welfare economic gain of 10.4 million € per year.

CONTENTS

2. BACKGROUND

The Danish EPA has proposed that NO_x emission from gas engines could be reduced in order to fulfil part of the Danish obligations in the NEC directive. Today, engines are adjusted to meet the demands given by regulations and to obtain the highest possible efficiency under these conditions. The NO_x target for 2010 was 127,000 ton per year. Today this target is met. The 2020 target is 79,640 ton/year. A recent projection of the NO_x emission in 2020 in Denmark is 82,999 ton/year /1/. This means that further action in terms of NO_x reduction is required. One source of NO_x emissions is the gas fired engines at decentralized power plants.

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 emissions than for others. Some correlations between emissions, efficiency and engine settings exist for early versions of lean-burn gas engines. New versions of lean-burn engines have been introduced and emission regulations have been changed. Therefore, most of the engines are now fitted with supplementary emission reduction equipment, mainly CO catalysts.

As a part of this work, eight engines were examined in order to examine the relation between different emissions from the engines and electrical and heat efficiency at different engine settings. Furthermore, the potential and consequences of NO_x reduction from natural-gas fired engine-based power plants in Denmark were assessed.

This work applies external cost for different components from /2/. The values for external costs given in /2/ related to NO_x emissions are a factor of 3.28 too high compared to the true values.

3. EXTERNAL COSTS RELATED TO EMISSIONS

External costs or externalities in relation to power production are defined as all costs that are not directly included in the price of the produced power. Health effects related to air pollution from power plants fall under this definition.

3.1. Health effects

The health cost externalities applied are calculated using the EVA model system (Economic Valuation of Air pollution) developed by Aarhus University, along the lines of the impact pathway chain originating from the ExternE project, see /1/.

The system consists of a regional-scale atmospheric chemistry transport model and a local-scale atmospheric transport model, 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 and are calculated for the chemical components. Based on the calculation 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 are calculated based on exposure-response relations derived from the literature. Finally, the associated costs in terms of direct and indirect costs for society are calculated.

The following health effects are 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. For further information and references refer to /2/, /3/.

3.2. Climate effects

Beside the CO_2, the content of methane and laughing gas (N_2O) present in the flue gas from natural gas fired engines acts as a climate gas. It is hard to valuate the effect of greenhouse gases. For the approach applied in this work the external costs related to these climate gases are accounted for by their relative greenhouse gas potential and the cost of CO_2 allowances.

DCE publishes aggregated data on emission factors (g/GJ) /4/, and for natural gas fired CHP engines for the climate gases they are:

CO_2: 57 kg/GJ
N_2O 0.58 g/GJ
CH_4: 481 g/GJ

The greenhouse gas potential of CH_4 and N_2O are 25 and 298, respectively /5/. This means that the effect of N_2O contributes about 0.3% of the total greenhouse gas emission from the gas engines despite its high greenhouse gas potential. Therefore, the effect of N_2O on greenhouse emissions can be neglected.

4. REDUCTION POTENTIAL FOR DIFFERENT ENGINE MODELS

One way of reducing emissions from gas fired engine based CHP plants is by changing the engine settings. A main advantage of the approach is that, in principle, it can be done without or with low investments. However, as stated in the introduction, adjusting an engine in order to reduce one emission often lead to increased emissions of other components, and the engine efficiencies are affected as well. These relations have been experimentally examined.

4.1. Natural gas fired engines

Eight different natural gas fired engines that are in operation on decentralized combined heat and power plants (CHP) in Denmark were examined. Makes and sizes of the engines are given in Table 1. The engines were selected in order to be representative of the natural gas engine based CHP production in Denmark. The eight examined natural gas fired engines represent 85% of the total natural gas consumption on natural gas engine based CHP units in Denmark.

Table 1 Make and size of the examined natural gas engines

Unit	Make	Size
#1	Rolls Royce B35:40	4,990 kW_e
#2	Rolls Royce KVGS-G4	2,075 kW_e
#3	Wärtsilä V25SG	3,140 kW_e
#4	Wärtsilä V34SG	6,060 kW_e
#5	Jenbacher J320	1,063 kW_e
#6	Jenbacher J620	3,047 kW_e
#7	Caterpillar G3516	1,047 kW_e
#8	Caterpillar G3616	3,845kW_e

For all examined engines, emissions and efficiencies were measured at different combinations of excess of air (λ) and ignition timing (IT). The excess of air and the ignition timing were set to obtain the following NO_x emission levels:

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

The level of NO_x emissions was chosen to match the present threshold limit given in the regulations for biogas and natural gas fired engines, respectively.

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

O_2, CO, CO_2, NO_x, NO_2 and UHC (unburned hydrocarbon).

Meters on the plants were applied for measurement of natural gas consumption, heat and electricity production.

A literature study showed that at concentration levels relevant for the exhaust gas from the engine there is no negative health effect related to emission of C_2H_6 and C_3H_8, and that negative health effect of formaldehyde is negligible compared to the effect of NO_x /2/.

4.1.1. Example of conducted measurements

The Rolls-Royce K engine is the most common engine model at natural gas fired CHP plants in Denmark /6/. The relation between NO_x emissions and the emissions of CO and unburned hydrocarbon (UHC) as well electrical and heat efficiency is shown in *Figure 1*. The figure shows that reduction of NO_x emissions lead to higher CO and UHC emissions as well as lower electrical efficiency and slightly higher heat efficiency. For further information on the conducted measurements please refer to /7/.

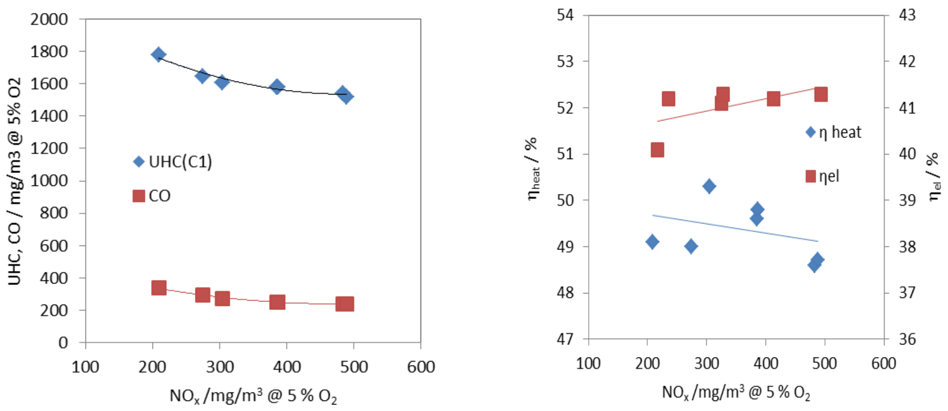

Figure 1 Relation between NO_x emissions, unburned hydrocarbon emissions (UHC) and CO emissions and heat and electrical efficiency for a natural gas fired Rolls-Royce K engine

In this work it is found that all examined engines will be able to operate with a NO_x emission of 250 mg/m^3 @ 5% O_2. However, for some engines it will be required to modify or replace the control system of the engine in order to obtain stable operation conditions.

5. REDUCTION POTENTIAL BY ENGINE ADJUSTMENT

Based on the conducted measurements, the potential of reducing the NO_x emissions from the natural gas fired engine based CHP units in Denmark is determined. In order to determine the potential of reduction it is necessary to know the emissions during normal operation. Data on emission levels and natural gas consumption for different gas engine was published in /6/ and these data is used in the presented work.

5.1. Yearly emissions from the examined engine models

In order to be able to determine the harmfulness of the exhaust gas it is not enough to know the actual concentration of the different species. Also the total flow of exhaust gas must be known in order to determine the amount emitted. The exhaust gas flow can be determined from the measured fuel and exhaust gas compositions as well as fuel consumption on a national level for the different engine models.

Besides the effect on the other emissions, the reduction of NO_x also affects the electrical and the heat efficiency of the engines as illustrated in *Figure 1*. The lower electrical efficiency at low NO_x operation of the engines means that the fuel consumption is increased in order to keep the power production constant. Totally, the fuel consumption for the gas engines will be increased by 1.5% if NO_x emissions are reduced from the present level to 250 mg/m^3. The reduction of NO_x emissions leads to a slightly higher heat efficiency. This combined with increased gas consumption means that the heat production will increase by 2.4% due to the NO_x reduction when the power production is kept constant.

Basically, all engine based CHP plants have boiler units installed as well, and most of the plants operate on market conditions. The heat demand of these plants is covered by engines if the electricity price is sufficiently high. If not, the heat is produced by boilers. In order to compensate the increased heat production from the engines due to the NO_x reduction it is assumed that the plants are equipped with natural gas fired boilers, and that the heat production for these are reduced accordingly in order to keep the heat production constant. A boiler efficiency of 105% based on lower heating value is applied. The reduced operation of the boilers leads to lower total emissions from these boilers. The effect on the emissions due to changed boiler operation is determined by using the emission factors given in Table 2.

Table 2 Emission factors for natural gas fired boilers (<50 MW). From /4/.

NO_x [g/GJ]	**CH_4** [g/GJ]	**CO** [g/GJ]	**CO_2** [kg/GJ]
42	0.1	28	57

The overall consequences of NO_x reduction by engine adjustment on fuel consumption and emissions are compiled and shown in Table 3. The figures in parenthesis are the reductions in percentage relative to the value before the NO_x reduction.

Table 3 Effect of reduction of NO_x emissions from the present level to 250 mg/m^3 @ 5% O_2 on other emissions from natural gas fired CHP engines in Denmark. The electricity production is kept constant.

	Reduction Engines only			**Reduction Engines and boilers**		
Natural gas	-359	TJ/year	(-1.5%)	-74	TJ/year	(-0.3%)
NO_x	1,237	ton/year	(40.0%)	1,248	ton/year	(40.3%)
CH_4	-1,255	ton/year	(-11.7%)	-1.254	ton/year	(-11.7%)
CO	-303	ton/year	(-19.0%)	-295	ton/year	(-18.5%)
CO_2	-16.5	mill. ton/year	(-1.3%)	0	mill. ton/year	(-0.03%)

6. DETERMINATION OF EFFECT ON EXTERNAL COSTS

For each of the engines #1 - #4 the external cost of different components in the flue was determined as described in section 3.1 /2/. The external costs were determined at the different operational conditions examined. The specific external cost – measured as €/kg – varied by around ±10% depending on examined plant and engine settings. The ±10% variation includes the influence of concentration level as well as height and geometry of outlet of the chimney. The specific external costs of the species, for which a negative health effect was found is shown in Table 4.

Table 4 Specific external costs for species with a negative health effect

NO_x €/kg ($NO_{2,eq}$)	**CO** €/kg	**HCHO** €/kg	**C_2H_4** €/kg
7.6	9.3 10^{-4}	1.3 10^{-3}	0.29

However, for gas engines the only health related external costs which are relevant to consider are the costs related to the NO_x emissions. The external costs for CO_2 and CH_4 are due to climate effects only. The health related external costs of the other components are negligible compared to the cost related to NO_x emissions, This is illustrated in Figure 2 showing the external costs related to electricity production for one of the examined engines.

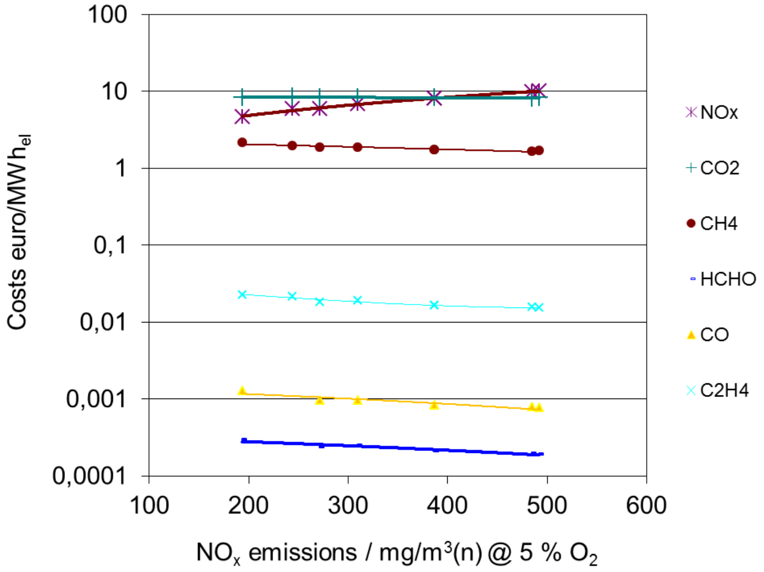

Figure 2 External costs related to electricity production for one of the examined engines. Note the logarithmic axis. CO_2 allowance price: 125 DKK/ton (16.3 €/ton).

It is of tremendous importance, which prerequisite is chosen regarding the external cost of greenhouse gases. The external cost related to emissions has been calculated with an allowance of 125 DKK/ton (16.6 €/ton). This price corresponds to the allowance price stated as part of the prerequisites for socio-economic analyses stated by the Danish Energy Agency for 2013 /8/. In comparison, the actual allowance price in the first part of 2013 was around 30 DKK/ton or 4 €/ton.

With the specific external costs of different components described above the effect of changed emissions due the NO_x reduction can be valuated. The consequences in terms of external costs due to changed emissions are given in Table 5. It is shown that the positive effect of NO_x reduction by far exceeds the negative impact it has on CH_4 emission, as the reduced NO_x emissions lead to a reduction in external costs of 9.5 M€, while the increased CH_4 emission results in extra external costs of 0.5 M€.

Table 5 Consequences on external costs related to emissions of reducing the NO_x emissions from natural gas fired CHP based engines from the present levels to 250 mg/m^3 (@ 5% O_2). CO_2 allowance price: 125 DKK/ton (16.3 €/ton).

		Before	**After**	**Reduction**
NO_x	**M€/year**	23.5	14.0	9.5
CH_4	**M€/year**	4.5	5.0	-0.5
CO	**M€/year**	0.0	0.0	0.0
CO_2	**M€/year**	21.1	21.1	0.0
Total	**M€/year**	49.2	40.2	9.0

7. WELFARE ECONOMIC ANALYSIS

A welfare economic analysis assessing the overall economic impact on society was conducted. As just shown, emission of harmful substances has negative consequences due to e.g. health effects and climate effects. However, that is not the only effect of a reduction of NO_x emissions by engine adjustment.

7.1.1. Fuel costs and maintanace

The NO_x reduction also leads to an increase in natural gas consumption. The natural gas could have been used elsewhere in the society and the increase in natural gas consumption should therefore be included in the analysis as a cost.

Operation of engines and boilers leads to service and maintenance costs. Gas engine service costs are normally paid according to a service contract that states a certain cost per produced MWh of electricity. The method applied in this work assumes constant power production. Therefore, the service and maintenance cost for engine operation is unaffected. The boiler operation is reduced corresponding to 285 TJ heat production, which leads to slightly lower maintenance costs.

7.1.2. Taxes

A change in emissions will lead to a change in taxes as both CH_4 and NO_x are subject to tax. Energy taxes are paid according to gas consumption. The tax depends on whether gas is used in engines or in boilers. CH_4 tax is only paid for the natural gas used in engines. CH_4 emissions from boilers are so low that they are not subject to taxation.

The reduction in NO_x emissions means a tax loss for the state and if the state’s expenses were to be unaffected, the tax loss should be covered by increasing other taxes. This leads to a so-called Tax Distortion Loss which is 0.2 € per € collected through compensatory tax increases. This is the welfare economic loss due to changed taxes.

The total welfare economic consequence of NO_x reduction by means of engine adjustment is 7.6 M€ per year for Denmark as a whole calculated as the difference between the welfare economic gain caused by reduced external costs and the welfare economic costs of increased natural gas consumption and lost tax incomes.

7.2. Discussion of the welfare economic analysis

Valuation of the health consequences and especially valuation of changes in mortality resulting from changes in NO_x emissions included in the standard price of NO_x is open to discussion. In fact, the standard price depends to a considerable extent on the welfare value of changes in mortality, and this value is highly uncertain. Therefore, the welfare economic net gain of optimising NO_x emissions is almost equally uncertain, as the effect of external costs due to NO_x emissions contributes to an 85% total welfare economic net gain.

8. REFERENCES

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