Environmental optimisation of natural gas fired engines

Main author
Torben Kvist
Danish Gas Technology Centre
Denmark
tkv@dgc.dk

Co-authors
Lise M. Frohn
National Environmental Research Institute,
Aarhus University
Denmark

Lars Jørgensen
Danish Gas Technology Centre
Denmark

International **G**as Union **R**esearch **C**onference - IGRC, 19-21 October 2011

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 NOx 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 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 harm caused by emissions from natural gas combustion. However, only health and climate effects are included. Externality 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. By reducing the NOx emissions to 40 % of the initial value (from 500 to 200 $mg/m^3(n)$) 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 usually 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. It was found that at high NO_x emission levels (500 mg/m^3n at 5 % O_2) the external costs related to the NOx emissions are 15 to 25 times the costs related to UHC emissions. At low NOx emission levels (200 mg/m^3n at 5 % O_2) the costs related to NOx 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 NOx emissions.

C O N T E N T S

1. Abstract 2

2. Introduction 4

3. Measurements 4

4. Externalities 6

5. Influence of engine settings on extenalities 7

6. Conclusions 8

7. Acknowledgement 9

8. References 10

2. INTRODUCTION

The Danish EPA has proposed that NOx emissions from gas engine plants are 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, NOx reducing engine adjustments affect other properties such as CO and UHC emissions as well as electrical and heat efficiency.

The gas fired 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 NOx emissions. Increasing the excess of air leads to lower combustion temperature and thereby also lower NOx 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 the 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 NOx than for others. 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 cost for society. The cost of damages caused by NOx 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. 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 specific NMVOC emissions from natural gas fired engines will be determined and incorporated in the calculation of the total cost of the environmental impact caused be emissions from natural gas fired engines for CHP production.

3. MEASUREMENTS

Four different natural gas fired engines were chosen for measurement of emissions as well as 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 kWe
#2	Rolls Royce KVGS-G4	2075 kWe
#3	Wärtsilä V25SG	3140 kWe
#4	Wärtsilä V34SG	6060 kWe

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.

For all four engines, emissions and efficiency were measured at different combinations of excess of air (□) 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]

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

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

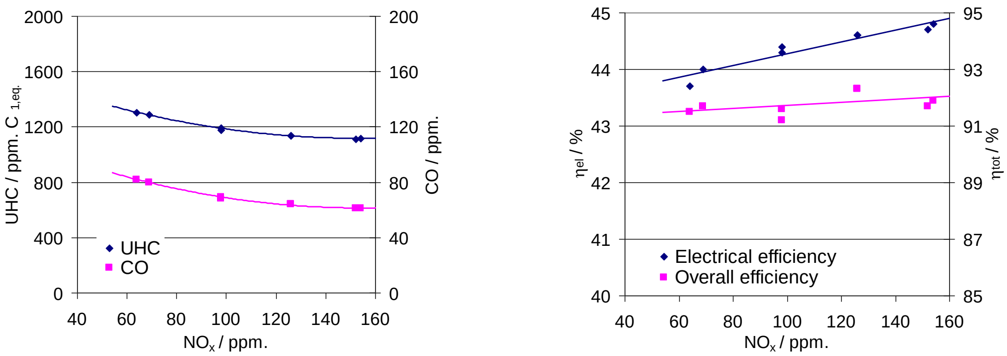

Figure 1 Emissions and efficiencies for the examined engine settings. Unit #1

[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

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

The measurements are described in detail in [3].

4. EXTERNALITIES

The health cost externalities are calculated using the EVA model system (Economic Valuation of Air pollution [4], [5], [6] and [7]) developed at the National Environmental Research Institute (NERI) - Aarhus University along the lines of the impact pathway chain originating from the ExternE project [8] - [11], see Figure 2.

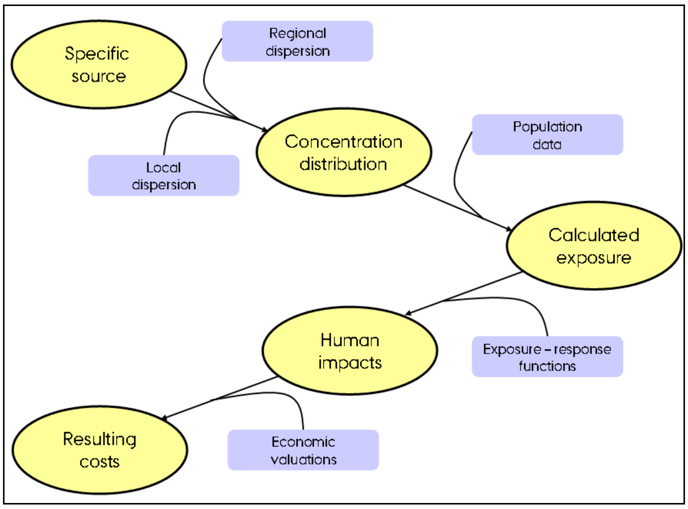

Figure 2 The ExternE impact - pathway approach for calculation of externalities from site-specific emissions of air pollutants. The regional dispersion in the EVA system is calculated with the DEHM model and the local dispersion is calculated with the OML-Multi model.

The system consists of a regional scale atmospheric chemistry transport model (the Danish Eulerian Hemispheric Model, DEHM, [12]) and a local scale atmospheric transport model (the Operational Meteorological Model, OML, [13]) 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 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.

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.
The externality costs or socio economic costs varies as shown in Table 2 for the individual species depending on engine make, engine settings and location of the CHP plant.

Table 2. Socio economic costs related to emissions from examined CHP plants.

	Effect	€/kg
NO_x	health	17 – 26
CO	health	$6{,}5\ 10^{-4}$ – $1{,}3\ 10^{-3}$
HCHO	health	$6{,}5\ 10^{-4}$ – $2{,}3\ 10^{-3}$
C_2H_4	health	0,16 – 0,44
CO_2	Climate	0,017
CH_4	Climate	0,35

5. INFLUENCE OF ENGINE SETTINGS ON EXTENALITIES

From the measured emissions and the specific costs of externalities related to the emissions, it is possible to determine the effect of changing engine settings on externalities related to the emissions.
Figure 3 shows the cost of externalities for the related production of 1 MWh of electricity for the different emissions for one of 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 an expected price of tradable CO_2 permits of about 17 € per ton.

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

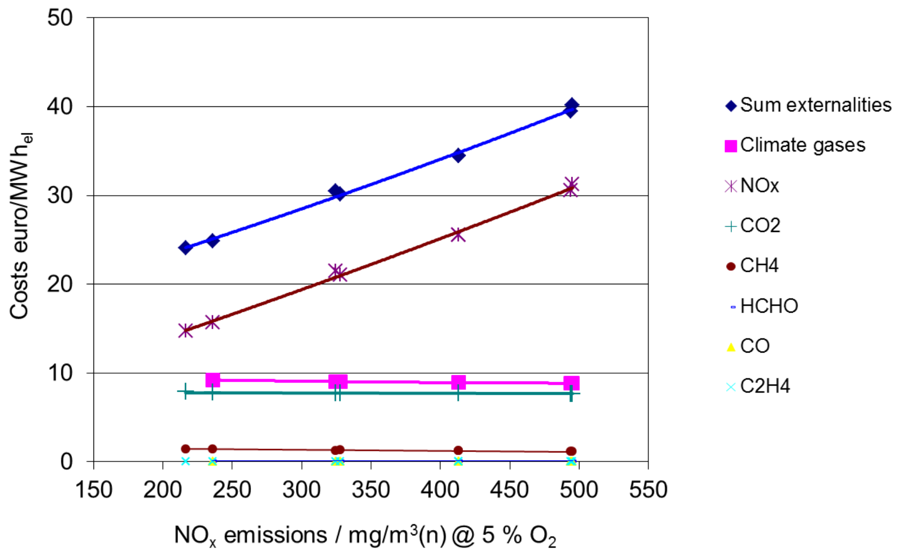

Figure 3 Specific cost of externalities for engine unit #1.

As previously mentioned there is a trade-off between NOx emissions and UHC emissions. If the engine is adjusted in order to reduce NOx emissions, the emission of UHC increases and vice versa. The figure shows that at a high NOx emission level - 500 mg/m^3n @ 5 % O_2 - the costs related to NOx are 15 to 25 times higher than the costs related to UHC emissions. At low NOx emission level - 200 mg/m^3n @ 5 % O_2 - the costs related to NOx 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 NOx emissions. It was found that the costs related to harm caused by NOx 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.

Reducing NOx 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 externalities represent between one third and two thirds of the socio-economic value of the natural gas. As the electrical efficiency is only decreasing marginally (see Figure 1) due the NOx reduction, the welfare economic value of the health effects more than compensates for the increase in gas consumption.

In Figure 4 the sum of the included externalities, the socio-economic value of natural gas and the sum of the two are shown for one of the four examined engines.

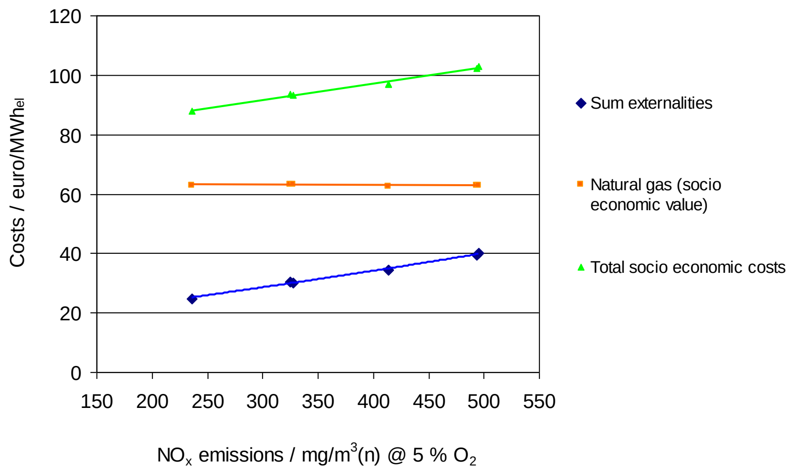

Figure 4 Specific cost of externalities, the socio-economic value of natural gas and the sum of the four examined engines. Medium exposure level.

6. CONCLUSIONS

For four different stationary natural gas fired engines located at decentralized CHP plants in Denmark emissions and efficiencies were measured at different engine settings leading to different NOx emissions.

It was found that

- Emissions of unburned hydrocarbons (UHC), CO and HCHO increase with decreasing NOx emissions.

- By reducing the NOx 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.
- Health related externality costs for the constituents NO_x, CO, C_2H_4 and HCHO were assessed. Based on these costs as well as costs related to the climate gases CO_2 and CH_4, the externality costs related to electricity production for the four examined gas engines were determined. 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 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 HCHO emissions at all examined cases.
- 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.

7. ACKNOWLEDGEMENT

The work is financially supported by Energinet.dk as a part of the PSO Forsk-EL programme and by the Danish natural gas distribution companies DONG Gas Distribustion A/S, HNG I/S, Naturgas Midt-Nord I/S and Københavns Energi A/S. Wärtsilä Denmark and Rolls-Royce Denmark are acknowledged for their participation.

8. REFERENCES

[1] Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants.

[2] Wit, J. d. and Christensen, O.” Various parameters influencing efficiency of and emission from high efficient gas engines”. IGRC 1995.

[3] Environmental optimisation of natural gas fired engines.

Measurement on four different engines. DGC report June 2010.

[4] Andersen, M.S., Frohn, L.M., Jensen, S.S., Nielsen, J.S., Sørensen, P.B., Hertel, O., Brandt, J. og Christensen, J., 2004, Sundhedseffekter af luftforurening – beregningspriser, DMU Faglig rapport 507, Danmarks Miljøundersøgelser, 85 s.

[5] Andersen M. S, Frohn L. M, Brandt J., Jensen S.S., 2007: External effects from power production and the treatment of wind energy (and other renewables) in the Danish energy taxation system. In: Critical Issues in Environmental Taxation: International and Comparative Perspectives Volume IV (Deketelaere K, Milne JE, Kreiser LA, Ashiabor H, eds). Oxford University Press, 319-336.

[6] Frohn, L. M., J. Brandt, O. Hertel , J. H. Christensen, C. Geels, M. S. Andersen, J. S. Nielsen, J. Frydendall, M. Hvidberg, S. S. Jensen, J. Petersen and P. V. Madsen, 2006: Assessment of air pollution related damages on human health – and the subsequent costs. Proceedings from the 3rd GLOREAM/ EURASAP Workshop, Modern developments in modelling and chemical data analysis, The Netherlands, September, 2005. pp. 8

[7] Frohn, L. M., M. S. Andersen, C. Geels, J. Brandt, J. H. Christensen, K. M. Hansen, J. S. Nielsen, O. Hertel, C. A. Skjøth and P. V. Madsen, 2007: “EVA - An integrated model system for as-sessing external costs related to air pollution emissions. A contribution to ACCENT T&TP”, Proceedings from the 2nd ACCENT Symposium, pp. 10.

[8] European Commission, 1995: "ExternE – Externalities of Energy", vol. 1-6, Bruxelles.

[9] European Commission, 1999: "ExternE – Externalities of Energy", Methodology annexes, Appendix I: The Ecosense model, Bruxelles. http://externe.jrc.es

[10] European Commission, 2002: "External costs – research results on socio-environmental damages due to electricity and transport", EUR 20198, Brussels.

[11] Holland, M., Berry J. and Forster, D., eds. 1999: "ExternE Externalities of Energy Volume 7: Methodology 1998 Update", European Commission, Directorate-General XII, Science, Research and Development. Brussels.

[12] Christensen, J. H., 1997: The Danish Eulerian Hemispheric Model – a three-dimensional air pollution model used for the Arctic, Atm. Env., 31, 4169–4191.

[13] Olesen, H. R., Løfstrøm, P., Berkowicz, R. and Jensen, A, B., 1992: “An improved dispersion model for regulatory use – the OML model”, in: Air Pollution Modeling and its Application IX, H. van Dop and G. Kallos (Eds.). Plenum Press, New York.

[14] Environmental optimisation of natural gas fired engines - calculation of health externalities. Frohn et al., NERI-AU report October 2010.