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Report

Efficiency evaluation of gas fuelled and electric driven buses in the public transport sector

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ABSTRACT
The following report evaluates the efficiency of gas fuelled and electric driven buses in the public transport sector on a theoretical basis. The results indicate that the combination of CHP power plants and electrical buses reach an overall efficiency of about 56% throughout the production chain (Well-to-Wheel), while this value is only about 30% for gas fuelled buses. The overall Well-to-Wheel efficiency further decreases to around 28% if the CHP power plant is replaced by a conventional gas turbine without heat recovery.
The CO_2-emissions are evaluated based on the example of a "Volvo B10L CNG" gas bus and the electric driven "Eurabus 600". The low energy consumption of the electric driven bus results in CO_2-emissions of only 181.4 gCO_2/km (Grid-to-Wheel). Depending on the utilised power plant technology the overall CO_2-emissions (Well-to-Wheel) amount to 323.9 gCO_2/km for a CHP power plant and 647.8 gCO_2/km for a conventional gas turbine.
On the other hand, gas fuelled buses emit about 1.25 $kgCO_2$/km (Tank-to-Wheel), which is eightfold the emissions of an electrical bus. The Well-to-Tank emissions further increase to about 1.32 $kgCO_2$/km.
The results indicate that the combination of CHP plants and electrical buses provide a much higher efficiency while reducing CO_2-emissions.

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Table of contents

1 Introduction

To reduce air pollution and CO_2 emissions, especially in urban areas, local authorities and public transport companies gradually replaced diesel fuelled with gas driven buses.

The use of natural gas, either as CNG (Compressed Natural Gas) or LNG (Liquefied Natural Gas), has been the first commonly available technology and a true alternative to diesel buses. Mainly ecological aspects, e.g. the reduction of NOx, particulate and noise emissions have been the main driver for the assignment of buses with gas-combustion engines. However, with the introduction of improved EU emission standards (Euro 1-6) and the improvements in the Diesel technology, the ecological advantage of CNG-buses decreases.

The use of natural gas through highly advanced CHP (Combined Heat and Power) plants delivers a better ecological utilization than its direct usage in gas-combustion engines. Electrical buses using the produced electricity from CHP power plants might therefore be a more efficient alternative than buses with gas-combustion engines. However, the development of pure electric driven buses is still in its initial phase since most manufactures, e.g. Scania, MAN and Volvo focused on the development of hybrid systems or an efficiency increase of already existing combustion technologies.

This report compares the efficiency of gas fuelled and electric driven busses using power from a CHP power plant. Furthermore, the CO_2 emissions are calculated for two particular cases using the available data for the "Volvo B10L CNG" gas bus and the electric driven "Eurabus 600".

2 Technical description

The following chapter includes a basic description of a CHP power plant and the characteristic values for gas fuelled and an electric bus used for the emission calculations.

2.1 Combined heat and power (CHP)

Combined heat and power plants are based on a sequential or a simultaneous generation of power (electricity) and heat in a single/ integrated system. Within the integrated system the current production of power and heat can be adjusted to the actual needs of the end user.

The most common CHP configurations are:

- Gas turbine with heat recovery unit (see Figure 1)
- Steam boiler with steam turbine

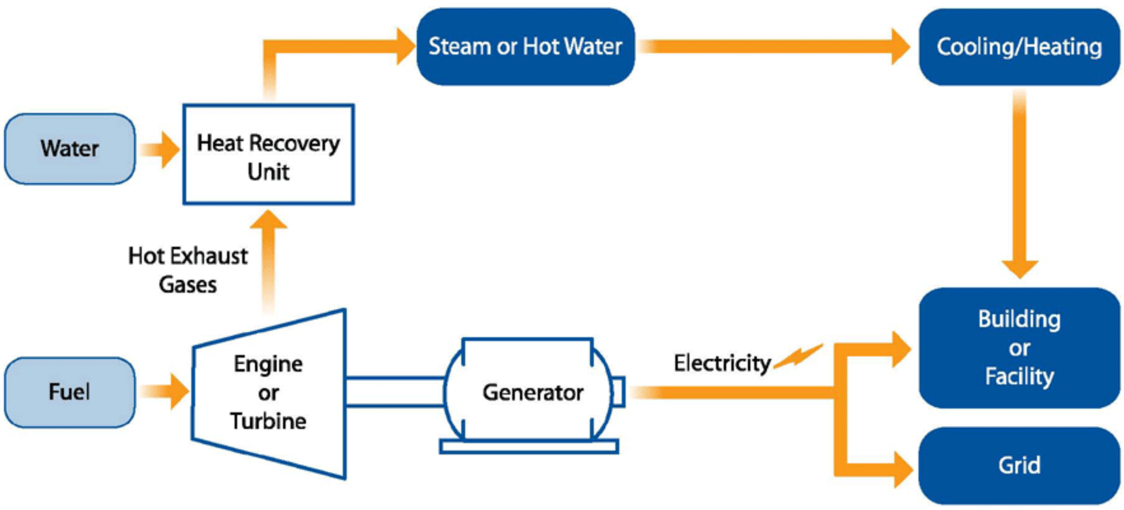

Figure 1 Gas turbine with heat recovery unit [12]

The results and assumptions in this report refer to the gas turbine with heat recovery configuration.
Gas turbines are available in various sizes ranging from about 500 kW up to 700 MW and can operate on a variety of fuel types including natural gas, synthetic gas, landfill gas and fuel oils.
In the CHP process the hot exhaust from the gas turbine is used to heat up water in the heat recovery unit. The resulting steam or hot water is commonly used for district heating in the surrounding areas. While simple gas turbines for power-only generation reach efficiencies of up to 40%, the CHP approach of a gas turbine with heat recovery reaches efficiencies between 70% and 80%.

2.2 Gas fuelled bus

As a benchmark case, the gas bus Volvo B10L CNG used by Skyss in the Bergen area has been chosen. Even though this type of bus has already been partially replaced by newer gas-driven buses from Mercedes, the available consumption data in [6] is a realistic indicator for the actual gas consumption in the everyday-use.

Manufacturer:	Volvo
Weight:	unknown
Length:	12.0m
Seats:	37
Average Consumption:	$0.547 Sm^3/km$

2.3 Electric driven bus

So far, the assignment of electrical driven buses using on-board batteries in the public transportation sector is rare. This mainly results from the restrictions imposed by the limited vehicle range, battery charging times, battery lifecycles and costs. Furthermore, the large producers of public buses, e.g. Volvo, Scania, MAN have mainly focused on the manufacturing of gas driven or hybrid buses instead of purely electric driven vehicles. Nevertheless, there are some examples in Germany where e-busses are in daily use in the public transport sector. The “Eurabus 600” used in the German city of Hamburg is selected as an example for the following calculations [3].

Manufacturer:	EURACOM GmbH
Weight:	17.5 t
Length:	11.48 m
Seats:	42
Battery:	$LiFePO_4$
Battery capacity:	630 Ah
Average consumption:	0.9 kWh/km
Theoretical range:	206 km

3 Efficiency

The following chapter includes a description of the life cycle assessment and the calculation of the overall efficiency for gas fuelled and electric driven buses.

3.1 Life cycle assessment (LCA)

Life cycle assessment is commonly used to describe the efficiency and the environmental impacts of fuel products. The assessment can be split up into various consecutive phases or steps, from the raw material to the final use in the vehicles. The life cycle of fuel products are typically divided into:

Well-to-Wheel is the typical life cycle assessment (LCA) for fuel and vehicles. It includes the total energy consumption of a vehicle, including the production and transport of the according fuel type. It therefore is the sum of the Well-to-Tank and the Tank-to-Wheel efficiency.

Well-to-Tank describes the efficiency and the total energy consumption necessary for the fuel production, so from the drilling hole to the tank. It is a measure of how much energy is necessary during the fuel production and distribution process.

Tank-to-Wheel or **Grid-to-Wheel** describes the internal efficiency of a vehicle. For vehicles with combustion engine this is the most important measure to identify possible losses and the overall efficiency. The fuel consumption and the manufacturer's information are based on standardized test cycles, e.g. the Dutch urban bus driving cycle and the Braunschweig-cycle [9]. However, these test cycles and their results are theoretical values. The real consumption and efficiency of vehicles, independent of the according fuel type, is largely influenced by external influences, e.g. driving speed, acceleration, temperature, vehicle weight and steepness of the road.

3.2 Efficiency of electrical busses

For the calculation of the Well-to-Wheel efficiency of electric vehicles the whole production and conversion chain has to be taken into consideration. The Well-to-Wheel efficiency is composed of the Well-to-Tank and the Grid-to-Wheel efficiency (see Figure 2).

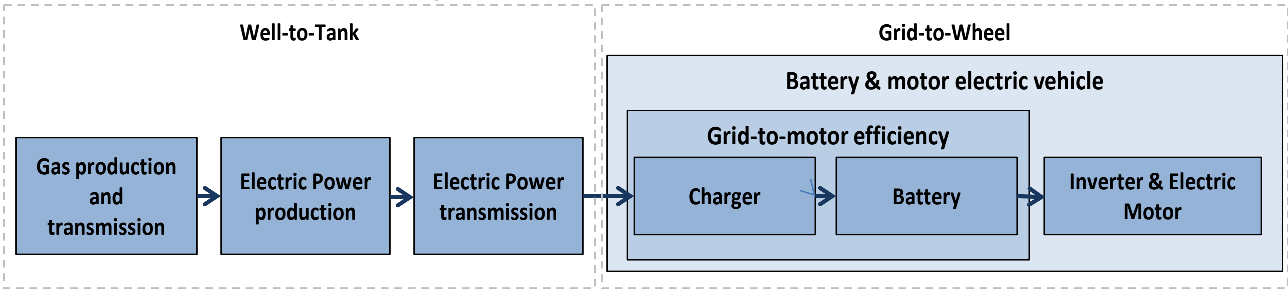

Figure 2 Well-to-Wheel production chain for electric busses

The Well-to-Tank efficiency includes the gas recovery, the electric power generation and the power transmission to the vehicle or loading station. Natural gas recovery including the gas production and the transmission to the gas tanks is assumed to have and overall efficiency of 95% [5].

The efficiency of the power production in a CHP power plant is largely dependent on the operational status, meaning how much of the initial energy is used for electricity production and how much for water heating. The numbers in [12] propose an efficiency between 70% and 80% for the most modern CHP power plants. A median value of 75% is chosen for the further calculations. For conventional gas turbines without heat recovery, the efficiency can reach values of up to 40%. In the calculations a value of 37.5% is assumed, reflecting the efficiency of a medium sized gas turbine with an installed capacity of 47 MW [1].

The electric power transmission losses are assumed with 8%, giving an overall efficiency of 92% including the power conversion in the transformer stations and the transmission lines [5].

The Tank-to-Wheel (Grid-to-Motor) efficiency for electric vehicles is depending on the efficiency of charger and battery. Both are assumed to be 93% resulting in an overall internal Grid-to-Motor effectiveness of 86% [7].

Taking both, the Well-to-Tank and the Tank-to-Wheel efficiency into account, the total Well-to-Wheel efficiency becomes 56% for a highly efficient CHP power plant (see Equation (1.1)).

$$0.95 \times 0.75 \times 0.92 \times 0.86 = 0.56 \tag{1.1}$$

For conventional gas turbines the total Well-to-Wheel efficiency is reduced by about 50% in comparison to the CHP scenario. Therefore, the total efficiency is only about of 28% (see Equation (1.2)).

$$0.95 \times 0.375 \times 0.92 \times 0.86 = 0.28 \tag{1.2}$$

Furthermore, the efficiency of electrical buses might be drastically reduced by the ambient temperature. Especially in the Norwegian climate a closer evaluation of the temperature dependency has to be made. Even though heating losses are already included in the assumed Tank-to-Wheel efficiency, the battery capacity and its efficiency are delicate to temperature variations. Figure 3 shows the temperature dependent storage capacity of the battery pack used.

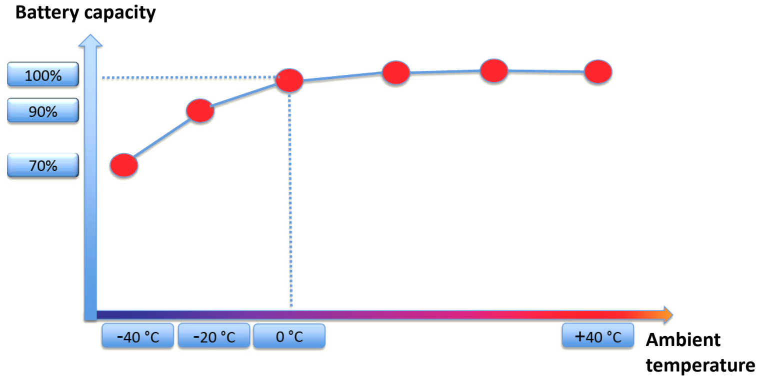

Figure 3 Temperature dependency of battery capacity [3]

3.3 Efficiency of gas driven buses

The Well-to-wheel efficiency of gas fuelled busses includes the gas recovery, its transmission and the internal vehicle losses for gas storage and the combustion process (see Figure 4).

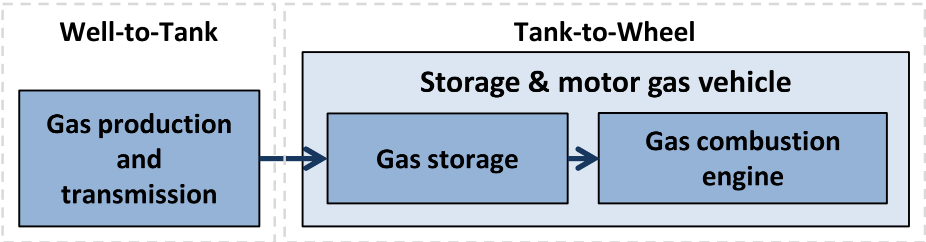

Figure 4 Well-to-Wheel production chain for gas driven busses

Similar to e-buses, the gas production and the gas transmission is included in the Well-to-Tank efficiency. Consequently, the efficiency is assumed to be 95%.

The Tank-to-Wheel efficiency includes losses during the refuelling and the losses in the combustion process. Even though modern gas-combustion engines can reach an effectiveness of up to 40% in the point of optimal operation [8], an efficiency of 32% is assumed to reflect a more realistic scenario [9].
Based on the assumptions made, the overall Well-to-Wheel efficiency becomes around 30% according to Equation 1.2.

$$0.95 \times 0.32 = 0.30 \tag{1.3}$$

4 Calculation of CO_2-emissions

The following chapter compares the CO_2 -emissions for the gas fuelled and the electric driven bus, based on the technical data for the Volvo B10L CNG and the Eurabus 600.

4.1 CO_2-emissions electric driven bus

For the calculation of the CO_2-emissions the following assumptions have been made based on the available data in [3][11]:

Density CNG:	0.840 kg/Sm^3
CO2 content:	201.6 g/kWh
Average consumption:	0.9 kWh/km
Annual driving distance:	40 000 km

According to Equation (1.4) the CO2-emissions for the electric driven bus are extremely little with a value of 181.4 gCO_2/km.

$$201.6\frac{gCO_2}{kWh}\times 0.9\frac{kWh}{km}=181.4\frac{gCO_2}{km} \tag{1.4}$$

However, the determined 181.4 gCO_2/km only represent the Grid-to-Wheel efficiency. When considering the whole production chain, the Well-to-Tank losses have to be included in the calculation. Thus, the Well-to-Wheel CO_2 –emissions increase to 323.9 gCO_2/km for a CHP power plant and 647.8 gCO_2/km for a gas turbine without heat recovery.

Assuming a driving distance of 40 000 km per year, the accumulated annual CO_2 -emissions for the CHP-electrical bus combination reach 7.3 tCO_2/a (Grid-to-Wheel) and 12.9 tCO_2/a (Well-to-Wheel) , respectively. Using electricity from a conventional gas turbine, the Well-to-Wheel CO_2 -emissions increase to 25.9 tCO_2/a.

4.2 CO_2-emissions gas driven bus

The calculation of the CO_2 -emissions for the gas driven bus is based on the data available in [3][9]:

Density CNG:	0.840 kg/Sm^3
CO_2 content:	2.727 $kgCO_2$/kg CNG
Average consumption:	0.547 Sm^3/km
Annual driving distance:	40 000 km

Based on the given data, the CO_2-emissions (Tank-to-Wheel) sum up to about 1.253 $kgCO_2$/km according to:

$$2.727\frac{kgCO_2}{kgCNG}\times 0.84\frac{kgCNG}{Sm^3}\times 0.547\frac{Sm^3}{km}=1.253\frac{kgCO_2}{km} \tag{1.5}$$

Taking the whole gas production chain into account, the total CO_2-emissions increase to 1.32 $kgCO_2$/km. The annual CO2-emissions per bus therefore become 50.0 tCO_2/a (Tank-to-Wheel) and 52.8 tCO_2/a (Well-to-Wheel), respectively.

5 Conclusion

This report evaluates the efficiency of gas fuelled buses and a CHP- electric bus combination. The results indicate that the CHP- electric buses reach an efficiency of up to 56% while emitting only 181.4 gCO_2/km (Grid-to-Wheel). The presented numbers for CO_2-emission are extremely low and in the vicinity of a modern upper class car (CO_2-emissions BMW 750 xd: 169 gCO_2/km [2]).

The results illustrate that the Well-to-Wheel efficiency is largely dependent on the power plant type used for electricity generation. While the Well-to-Wheel CO_2 –emissions only amount to 323.9 gCO_2/km for a CHP power plant, the low efficiency of only 28% of a conventional gas turbine increases the emissions to 647.8 gCO_2/km.

The overall Well-to-Wheel efficiency of gas fuelled buses is only about 30%. The main losses occur in the combustion process of the engine where the main share of the available energy stored in the gas is converted into heat instead of kinetic energy. The CO_2-emissions (Tank-to-Wheel) are about 1.253 $kgCO_2$/km while the Well-to-Wheel emissions sum up to 1.32 $kgCO_2$/km.

A comparison of the presented numbers illustrates the advantages of the CHP-electric bus combination over gas busses. The higher Well-to-Wheel efficiency of e-busses results in very low CO_2-emissions only corresponding to one eight of the gas bus emissions.

6 Concluding remarks

A realistic assumption of CO_2-emission is largely dependent on external parameters, e.g. power plant efficiency, losses in the production chain etc. The applied values used for the efficiency and the emission calculation are based on relevant and reliable data sources. However, the numbers in [4] illustrate that more conservative assumptions will largely influence the results. The results in this report should therefore be used as an indicator for the efficiency of gas fuelled and electric driven buses.

Besides, the efficiency calculation does not include a full life cycle assessment taking the production, the use and the scrapping of gas fuelled and electric driven buses into account. The results in [10] illustrate that the production process has to be considered in a final evaluation of CO_2-emissions and vehicle efficiency.

7 References

[1] Siemes AG. Industrial Gas Turbines - The comprehensive product range from 5 to 50 megawatts. Technical report, 2012.
[2] BMW. http://www.bmw.de. Technical report, 2012.
[3] Eurabus. Eurabus 600 - batterielektrischer Stadtbus. Technical report.
[4] European Association for Battery Electric Vehicles. Energy consumption, co2 emissions and other considerations related to battery electric vehicles. Technical report, 2009.
[5] General Motors Corporations, Argonne National Laboratory, BP, ExxonMobil, Shell. Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - North American Analysis. Technical report, 2001.
[6] HOG energi. Biogass som drivstoff for busser- biogass fra nye biologiske råstoffkilder. Technical report, 2012.
[7] M. Tarpenning M. Eberhard. The 21st Century Electric Car. Technical report, Tesla Motors Inc., 2006.
[8] MAN. http://www.mantruckandbus.com/com/de/press___media/Pressemitteilung_165376.html, 2012.
[9] N. Clark-G. Rideout N.O. Nylund, K. Erkkila. Evaluation of duty cycles for heavy-duty urban vehicles. Technical report, West Virgginia University, Environment Canada, VTT, 2007.
[10] G. Majeau-Bettez A. Strømman T. Hawkins, B. Singh. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Technical report, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), 2012.
[11] Umwelt Bundesamt. Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix. Technical report, Federal German Ministry for the Environment, Nature Conservation and Nuclear Safety, 2007.
[12] U.S. Environmental Protection Agency Combined Heat and Power Partnership. Catalog of CHP Technologies. Technical report, U.S. Environmental Protection Agency Combined Heat and Power Partnership, 2008.

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