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Greenhouse gas emissions from heavy duty vehicles using upgraded biogas as a fuel

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Abstract

This paper examines the CH_4 loss and the total greenhouse gas emission (GHG emissions) savings associated with the use of upgraded biogas as a fuel for heavy duty vehicles in Denmark. The study focuses on the emissions related to the operation of the vehicles and the emissions from fuel tanking. Emission calculations are made in two scenarios for 2035 using low and high loss CH_4 input factors derived from the literature. Results suggest that engine loss/tank boil off is the largest source of CH_4 followed by CH_4 leaks at the fuel station and the CH_4 emissions from exhaust. The low[high] loss emission percentage shares are 57 %[62 %] for engine loss/tank boil off, 43 %[23 %] for fuel station and 0.4 %[15 %] for exhaust. The calculated low and high loss GHG emission reductions are 91 % and 86 % from "tank-to-wheel" (engine loss/tank boil off and exhaust) and 88 % and 84 % from "pump-to-wheel" (engine loss/tank boil off, exhaust and fuel station), in relation to the diesel reference scenario.

Key-words: CNG, LNG, CH_4, CO_2, biogas, heavy duty vehicles

1 Introduction

Today the transport sector almost entirely uses fossil fuels except for a few percent biofuels added, and electric vehicles generally penetrates the car market very slowly. In order to meet the global challenges in terms of climate protection, Denmark has adopted a climate law establishing the strategic frame for the transformation into a low carbon society by the year 2050. For road transport alone, a few technological solutions exist to achieve this political goal.

In the light vehicle segment of the road transport fleet, the technological development within battery electric vehicles and plug-in hybrids should allow

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passenger cars and vans to become mainly electric in the future. Also fuel cell cars powered by hydrogen is likely to penetrate the market in the future as they will provide driving range similar to nowadays cars. Trucks instead, will most likely not be electric in the future- except in small niches of the fleet and for limited applications - as they are too heavy and cannot be frequently charged during normal operational use. Urban buses on short distance routes and opportunities for fast charging as part of the timetable have a potential to become battery electric or battery/hybrid in the future. As a second likely alternative, trucks and buses can be using solely biodiesel, but in this case the provision of second-generation biofuels from Danish sources may be limited by the availability of bio-resources and might not be provided in the quantities needed.

Instead, natural gas (methane or CH_4) seems like the most promising fuel alternative for heavy duty vehicles in Denmark. Denmark has a large potential for biogas production from different organic sources, e.g. manure, straw and household waste, and after upgrading biogas can be distributed in the existing natural gas grid. Due to these advantages, there is a strong political, administrative and commercial interest for the deployment and use of biogas in Denmark. Since the Danish Government's plan for Green Growth in 2009 there is a political objective to use up to 50 % of the livestock manure in Denmark for energy production (probably primarily biogas) towards 2020. This goal was further pursued in the National Energy Agreement from 2012, supporting biogas development, and a task force was formed for realising the targets. In addition a resource strategy of the Danish Government from 2013 stresses that more organic waste from households, restaurants and grocery shops should be collected and used to produce biogas (Ministry of Environment, 2013; Danish EPA 2014).

Although major fossil fuel CO_2 emission savings can be achieved by using the CO_2 neutral natural gas produced from organic sources, loss and escapes of CH_4 also takes place through the whole chain from production, distribution of gas to fueling stations, at the fueling stations (stationary losses and during vehicle tanking) and during actual vehicle driving. CH_4 is a strong greenhouse gas and therefore the potential loss of CH_4 causes climate concerns.

This paper examines the CH_4 loss and the total greenhouse gas emission (GHG emissions) savings associated with the use of upgraded biogas as a fuel for heavy duty vehicles in Denmark. The study focuses on the emissions related to the operation of the vehicles and the emissions from fuel tanking. The emission consequences are calculated for the scenario year 2035, assuming a feasible new sales substitution of diesel vehicles by Euro VI CNG or LNG vehicles using natural gas produced from biogas. Emission calculations are made in two scenarios using low and high loss CH_4 input factors derived from the literature.

2 Method

2.1 Baseline fuel consumption forecast for heavy duty vehicles (diesel reference scenario)

The projected fuel consumption for Danish heavy duty vehicles (HDV's) until 2035 estimated in the current Danish national emission projections (Danish EPA project; report not published) constitutes the business as usual scenario in the present project (diesel reference scenario). The HDV's are grouped into rigid trucks, truck-trailers, articulated trucks and buses and are further stratified into weight categories and EU emission legislation levels according to the fleet description of the EU COPERT IV emission model (EMEP/EEA, 2015). The fuel consumption for each layer of the fleet is calculated as the product of vehicle number, and annual mileage (km) and fuel consumption factor (MJ/km) split into urban, rural and driving conditions. Fleet, mileage and trip speed data comes from the Technical University of Denmark and fuel consumption factors are taken from COPERT IV. Figure 1 shows the forecasted fuel consumption for rigid trucks, truck-trailer/articulated trucks (TT/AT trucks), urban buses and tourist buses. Figure 1 clearly shows how the Euro VI technology gradually becomes more and more important during the forecast period as older emission technologies gradually phase out. Correspondingly, in 2020, 2025 and 2030 the calculated Euro VI fuel consumption shares become 81 %, 96 %, 99 %, respectively.

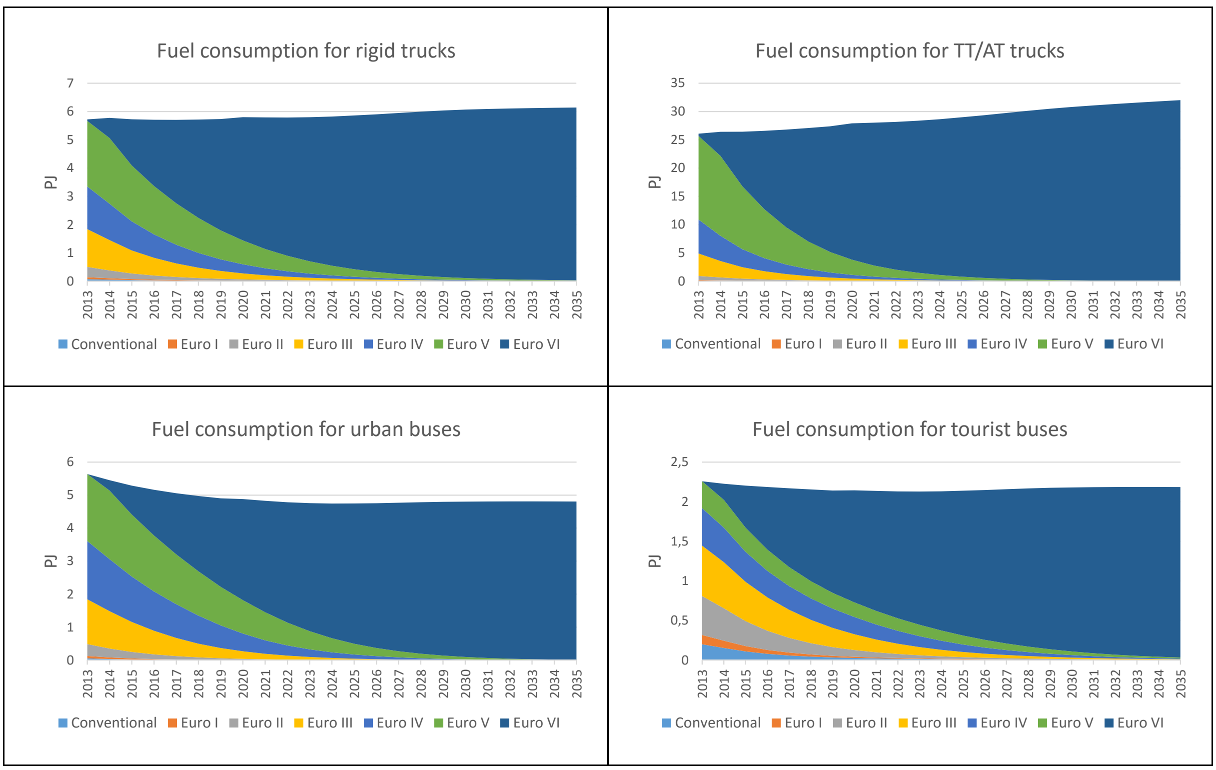

Figure 1. Forecast of fuel consumption (PJ) for heavy duty vehicles in Denmark until 2035.

Euro VI vehicles are relevant for natural gas substitution and therefore the fuel consumption picture is analyzed in more details for 2035. This is shown in Figure 2 (note the axis scaling).

The estimated total fuel consumption for Danish heavy duty vehicles becomes 45 PJ in 2035. The calculated fuel consumption (percentage shares in brackets) for TT/AT trucks, rigid trucks, urban buses and tourist buses are 32 PJ(71 %), 6.1 PJ(14 %), 4.8 PJ(11 %) and 2.2 PJ (5 %), respectively. A break down of fuel consumption by vehicle size categories for trucks shows the vehicle category 40-50t uses 21 PJ (46 %) and the vehicle category 34-40t 9.5 PJ (21 %). The fuel result figures are also shown in Table 2.

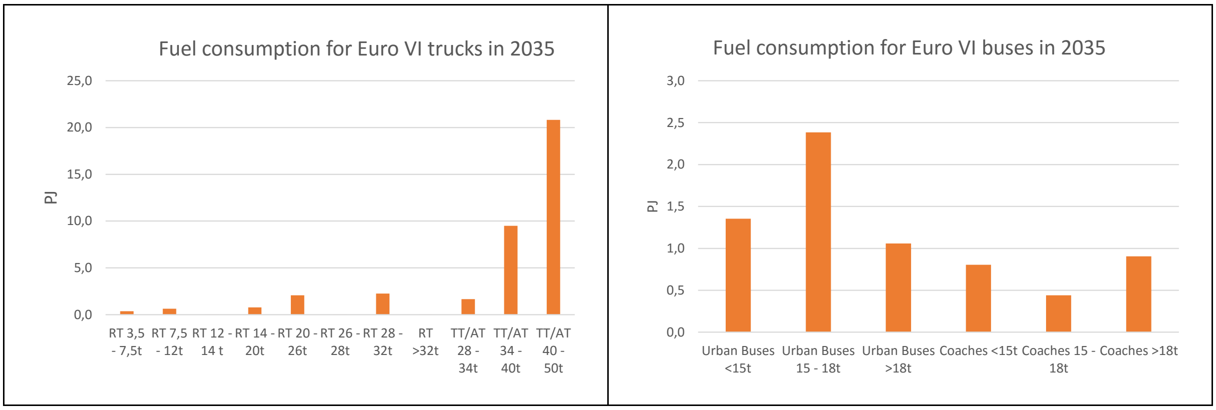

Figure 2. Forecast of fuel consumption (PJ) for Danish Euro VI trucks and buses in 2035.

2.2 CNG and LNG vehicles in the biogas scenario

CNG (Compressed Natural Gas) vehicles are available on the market today up to 320 hp (see e.g. www.gasbiler.info). The CNG vehicles have CNG fuel stored on board in pressurized tanks (200-260 bar) and are equipped with a SI (spark ignition) engine that operates similarly to a gasoline engine. Today's vehicles are certified as Euro VI and are equipped with a three-way catalyst to ensure compliance with the EU emission standards.

One disadvantage of CNG vehicles is the smaller km range between fuel stops compared to their conventional diesel counterparts. Another drawback for CNG is the relatively low fuel economy vs diesel. Only limited fuel economy data is currently available for Euro VI CNG engines to compare with diesel. Fuel economy data for Euro VI CNG vs. Euro VI diesel examined by Danish Technological Institute for the Danish Energy Agency (2014) showed large variations depending on vehicle model and emission test cycles. An average of 19 % more MJ/km for CNG compared to diesel could be derived from the data material[2]. However, it is believed that a future introduction of throttle-less gas engines will bring considerable fuel efficiency improvements maybe in the order of 15 % compared to today's CNG vehicles (e.g. Danish Energy Agency, 2014).

LNG (Liquefied Natural Gas) vehicles have fuel stored onboard in vacuum insulated storage tanks (3-10 bar, -160 ^{o}C). The LNG vehicles are equipped with dual fuel engines that operate similarly to a diesel engine and use 5 % diesel to pilot the ignition of fuel in the cylinder during each combustion stroke. Due to the higher energy density of the LNG fuel stored the km range between fuel stops for LNG vehicles is considerably longer than for CNG.

In Europe LNG sales have only recently started, and in Denmark only one LNG truck is available at the moment. LNG trucks are, however, more widespread in use in other parts of the world. This is e.g. the case in the United States, where a national network of public LNG fueling centres has been established with new LNG filling stations continuously being added to the network. The commercially available LNG dual fuel engines in the US today cover the entire engine size range for freight vehicles up to 600 hp. Although only certified for the US market the engines are equipped with SCR catalysts, DOC catalysts and DPF's in order to meet the most stringent US emission standards for heavy duty vehicles. In terms of fuel economy, LNG suffers from the same drawback as for CNG. The International Council on Clean Transportation (ICCT, 2015) estimate a 10 % lower fuel economy for LNG vehicles compared to their modern diesel counterparts.

By all means, LNG trucks will also become commercially available in Europe. The introduction of LNG for transport in Europe is not least supported by the adoption of the EU directive 2014/94 that places on member countries to establish a LNG tank facility infrastructure along the main arterial roads (TEN T: Trans European road network) in the EU by 2025.

In the present project CNG vehicles replace rigid trucks and buses and for TT/AT trucks the vehicle replacement is made with LNG trucks. For both CNG and LNG vehicles, a 10 % lower fuel economy compared to diesel is assumed in the biogas scenario calculations.

2.3 Emission factors and CH_4 loss factors

A fuel related CO_2 factor of 66.6 g/MJ is used in the diesel reference scenario. The factor rely on the country specific CO_2 emission factor of 74 g/MJ for neat diesel and the 10 % blend percentage of (CO_2 neutral) biodiesel in the diesel fuel assumed by the Danish Energy Agency for 2035. N_2O and CH_4 emission factors in the reference case come from COPERT IV.

[2] The same study found no significant NO_x and PM (Particulate Matter) emission differences between Euro VI CNG and diesel based on the limited measurement data available

The source of CH_4 emission factors for CNG vehicles is measurements made by Danish Technological Institute (DTI), see also DTI (2015). The latter study reports measurements of among others CH_4 for two CNG buses and one Euro CNG truck - all certified as Euro VI - obtained during chassis dynamometer tests using different test driving cycles. The measurements obtained during the World Harmonized Vehicle Cycle (WHVC) were selected as realistic values for the present study, and the measured emissions were believed to represent LNG vehicles also. high*[low]* emission percentages of 0.196*[0.003]* % CH_4 per unit of fuel consumed were derived from the measurements. An assessment of the measurement results for other emission components (CO, NMVOC) gave DTI reason to believe that the high emission factor was measured during rich fuel engine running conditions. Transformed into g/kWh the high factor equals 0.47 that is just below the Euro VI emission limit value of 0.5 g/kWh valid for natural gas engines.

In addition to direct CH_4 emitted from the tail pipe, other CH_4 emissions occur from CNG and LNG vehicles directly related to the vehicles. These sources of CH_4 have been summarized in the assessment study for heavy duty vehicle natural gas emissions made by ICCT (2015) and low/high emission factors are proposed based on the literature. The ICCT emission factors are adopted for the present study.

For CNG vehicles, CH_4 is emitted from the crankcase as so-called “blow by emissions” occurring from CH_4 leaking between piston rings and cylinder walls, being vented to the atmosphere. LNG vehicles use diesel-like HPDI (high pressure direct injection) engines, and in this case, CH_4 occasionally needs to be vented due to pressure control in the fuel injection system. In addition CH_4 from LNG vehicles is vented from the vehicle fuel tank during ”boil off” pressure release, which is made for safety reasons. In the following crankcase/dynamic venting/tank boil off emissions are referred to as engine loss/tank boil off emissions.

ICCT (2015) also propose factors for CH_4 leaks and escapes from natural gas fueling stations. CH_4 leaks occur from valves, pipes and fittings at the tanking facilities and small escapes of CH_4 occur during nozzle connection and disconnection during the tanking of the vehicles. In addition for CNG compressor loss occurs at the station, whereas for LNG, methane is boiled off in storage tanks and is manually vented from vehicle fuel tanks prior to refueling.

Table 1. CH_4 loss (% of fuel delivered).

Source of CH_4 loss	Low estimate	High estimate
Tail pipe exhaust	0.003	0.2
Engine loss/tank boil off	0.4	0.8
Fueling station	0.3	0.3

2.4 Calculation of CH_4 loss

The source specific emissions of CH_4 in the biogas scenario are calculated as follows:

$$E_{CH4} = \frac{FC_{GJ} \times 1.1}{LHV_{CH4}} \times LF_{CH4}/100$$

Where:

ECH_4 = Mass based emissions of CH_4 (tonnes)

FCPJ = Fuel consumption (GJ) for diesel vehicles in the reference scenario (Section 1.1, table 2)

1.1: Fuel economy adjustment factor for CNG/LNG vehicles replacing diesel vehicles (Section 1.2).

LHV_{CH4} = Lower heating value for CNG/LNG fuel (47.96 GJ/tonnes; Danish Energy Agency, 2014)

LF_{CH4} = Source specific loss factor of CH_4 (% of fuel delivered, Table 1)

3 Results

The emission results for the reference scenario and the biogas scenario are shown in Table 2.

Table 2. Emission results for the reference scenario and the biogas scenario.

	Reference scenario				Biogas scenario									
	FC	CO_2	CH_4	N2O	Fuel consumption				CO_2	CH_4 exhaust		CH_4 engine loss/tank boil off		CH_4 Fuel station
	PJ	kTonnes	Tonnes	Tonnes	CH_4 Tonnes	Diesel Tonnes	CH_4 PJ	Diesel PJ	kTonnes	low Tonnes	high Tonnes	low Tonnes	high Tonnes	Tonnes
Total Trucks	38.1	2540	5.1	189	837	41	40.1	1.8	117	25.1	1621	3347	6694	2518
RT	6.1	409	1.0	27	140	0	6.7	0.0	0	4.2	272	561	1121	422
TT/AT	32.0	2131	4.1	162	697	41	33.4	1.8	117	20.9	1350	2787	5573	2096
Total Buses	6.9	466	0.8	28	159	0	7.6	0.0	0	4.8	309	638	1275	480
Urban buses	4.8	320	0.5	20	110	0	5.3	0.0	0	3.3	213	440	880	331
Coaches	2.2	146	0.3	7	49	0	2.4	0.0	0	1.5	96	197	395	149
Grand total	45.0	3006	5.9	217	996	41	47.8	1.8	117	29.9	1930	3985	7970	2998

In Table 3 the emission results for the reference scenario and the biogas scenario are shown transformed into CO_2 equivalents by using the global warming potential factor of 25 for CH_4 and 298 for N_2O (IPCC, 2007).

Table 3. Emission results for the reference scenario and the biogas scenario counted in CO_2 eq.

	Reference scenario			Biogas scenario							
	CO_2	CH_4	N_2O	CO_2	CH_4 exhaust low	high	CH_4 engine loss/tank boil off low	high	CH_4 Fuel station	CH_4 Total low	high
	kTonnes CO_2-eq.			kTonnes	kTonnes CO_2-eq.		kTonnes CO_2-eq.		kTonnes CO_2-eq.	kTonnes CO_2-eq.	
Total Trucks	2540	0.13	56	117	0.63	40.5	83.7	167.4	62.9	147	271
RT	409	0.02	8	0	0.11	6.8	14.0	28.0	10.5	25	45
TT/AT	2131	0.10	48	117	0.52	33.7	69.7	139.3	52.4	123	225
Total Buses	466	0.02	8	0	0.12	7.7	15.9	31.9	12.0	28	52
Urban buses	320	0.01	6	0	0.08	5.3	11.0	22.0	8.3	19	36
Coaches	146	0.01	2	0	0.04	2.4	4.9	9.9	3.7	9	16
Grand total	3006	0.15	65	117	0.75	48.3	99.6	199.2	74.9	175	322

Measured in CO_2 equivalents the low and high estimates of CH_4 loss for the biogas scenario become 175 ktonnes and 322 ktonnes, respectively (Table 3 and Figure 3). The CH_4 losses from each source are proportional to their fuel related emission factors (Table 1), and needless to say, for each source category the internal emission shares correspond with the fuel consumption share per vehicle category. In both cases the engine loss/tank boil off is the largest source of CH_4 followed by CH_4 leaks at the fuel station and the CH_4 emissions from exhaust. Derived from the numbers in Table 3, the engine loss/tank boil off*[fuel station, exhaust]* emission shares are 57 %*[43 %, 0.4 %]* and 62 %*[23 %, 15 %]* in the low and high case, respectively.

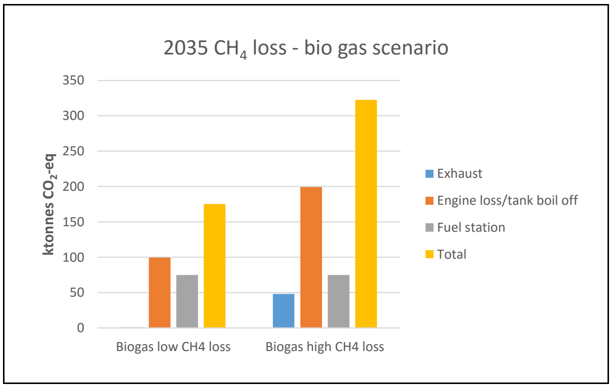

Figure 3. Total CH4 loss (ktonnes CO2 eq.) from Danish heavy duty vehicles calculated in the biogas scenario for 2035.

The total GHG emissions calculated in the low/high biogas scenarios are shown in Figure 4 for the "tank-to-wheel" (engine loss/tank boil off and exhaust) and "pump-to-wheel" (engine loss/tank boil off, exhaust and fuel station) chain of emissions. The CO_2 emissions calculated in the biogas scenario originates from the 5 % diesel pilot fuel (explained in Section 1.2). Due to lack of emission information, the diesel heavy duty N_2O emission factors are used for the gas vehicles as well.

The calculated low and high loss GHG emission reductions are 91 % and 86 % from tank-to-wheel and 88 % and 84 % from pump-to-wheel, in relation to the diesel reference scenario.

For tank-to-wheel the calculated low*[high]* GHG percentage contributions for CO_2, CH_4 and N_2O become 42 %*[27 %]*, 36 %*[58 %]* and 23 %*[15 %]*, respectively. In the pump-to-wheel case, the low*[high]* CO_2, CH_4 and N_2O GHG contributions become 33 %*[23 %]*, 49 %*[64 %]* and 18 %*[13 %]*.

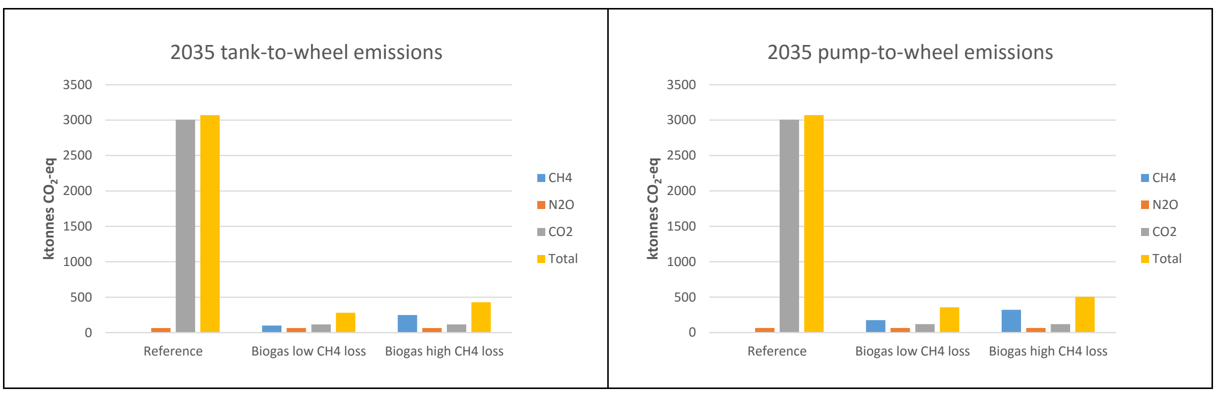

Figure 4. Total tank-to-wheel and pump-to-wheel greenhouse gas emissions (ktonnes CO2-eq.) for Danish heavy vehicles in 2035 calculated in the reference scenario and the biogas scenario.

4 Conclusion

This paper examines the CH_4 loss and the total GHG emissions savings associated with the use of upgraded biogas as a fuel for heavy duty vehicles in Denmark. The study focuses on the emissions related to the operation of the vehicles and the emissions from fuel tanking. Emission calculations are made in two scenarios for 2035 using low and high loss CH_4 input factors derived from the literature.

Results suggest that engine loss/tank boil off is the largest source of CH_4 followed by CH_4 leaks at the fuel station and the CH_4 emissions from exhaust. The low*[high]* loss emission percentage shares are 57 %*[62 %]* for engine loss/tank boil off, 43 %*[23 %]* for fuel station and 0.4 %*[15 %]* for exhaust.

The calculated low and high loss GHG emission reductions are 91 % and 86 % from "tank-to-wheel" (engine loss/tank boil off and exhaust) and 88 % and 84 % from "pump-to-wheel" (engine loss/tank boil off, exhaust and fuel station), in relation to the diesel reference scenario.

The input data for CH_4 loss are regarded as relatively uncertain (ICCT, 2015) and the resulting emissions might change if new CH_4 loss factors become available.

The GHG emissions calculated from tank-to-wheel are small in comparison with the emissions from the diesel reference scenario, and the GHG emissions are still quite low even if we include the CH_4 loss from the fueling stations (pump-to-wheel emissions). As a side remark, the calculated GHG emissions will be additionally 4 percent point lower by assuming that the LNG pilot fuel consist of neat biodiesel rather than diesel with a 10 % content of biodiesel, based on the energy forecast from the Danish Energy Agency.

To gain a complete overview of the total GHG emission consequences of a 100 % fuel switch from diesel to natural gas for heavy duty vehicles, we need to estimate the emission loss during the production of the natural gas from biogas, distribution of gas to fueling stations and the changed emissions in the society due to the use of bio resources for biogas production instead of alternative usage.

Jørgensen & Kvist (2015) examined the CH_4 loss during the production of biogas. Measurements made at nine biogas plants showed a significant average loss of 4.2 % of the produced biogas quantity. A subsequent work made to seal the leaks discovered brought down the CH_4 percentage loss to 0.8 % (Agrotech, 2015). By using 0.8 % and 4.2 % as low and high CH_4 loss factors, respectively, for biogas production, the "production-to-wheel" (excluding gas distribution) GHG emission reductions are roughly estimated to 82 % and 50 % compared with the diesel reference scenario.

On the other hand, the upstream Danish emission savings from alternative usage of the bio resources will be very large. A large amount of the bio resource is foreseen to consist of manure from animal production that consequently will not emit methane from the various manure management steps, including in stables and storage tanks.

The upstream emission loss during natural gas production and plant to fueling station distribution, and the emission savings from alternative bio resource usage will be investigated in an ongoing project carried out at Danish Centre for Environment and Energy (DCE), Aarhus University that the present study is also part of.

Acknowledgments

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