1. Introduction

Biogas is in many ways an interesting fuel as it can be produced from rest products, is clean and if burned in a controlled fashion can provide a considerable utility for the climate. The agricultural sector has a great potential for biogas production. In order to realise that potential it has to be profitable to produce the gas. A major economic issue is the cost of upgrading the gas, i.e. the cost of removing carbon dioxide as well as other contaminants. The purpose of this project was therefore to investigate the impact of using gas with less methane/more carbon dioxide in agricultural vehicles from a systems perspective. If such a gas is used the cost for upgrading can be reduced, potentially providing an economic benefit for the plant owner and an environmental benefit for society at large.

2. Background

When biomass is digested in the absence of oxygen methane and a variety of gases will form. If the process is controlled and uses biological material from farms as source material it will produce a gas mixture that contain 55-70 % methane, the rest being mostly carbon dioxide, but with some fraction of contaminants. This gas contains enough energy to allow it to be used in combustion engines to produce power, where it is converted to carbon dioxide and water. It can either be used locally to produce heat and electricity or it can be used to run vehicles. The latter has the advantage of making the gas a higher value product as it competes with more expensive products such as petrol and diesel rather than fuel oil and wood products.

Biogas has been purified to fuel quality since the 1990s. As of 2011 there are more than 220 upgrading facilities in the world, of which about 55 are in Sweden. The most common general principles used to upgrade biogas are (Bauer et al, 2011):

- Amine scrubber: Amine reacts chemically with carbon dioxide to capture it from the flow. In order to later release the carbon dioxide the amine has to be heated whereupon the reaction runs backwards.
- Membranes: Biogas is pressurized and a membrane lets most of the carbon dioxide through whilst containing most of the methane.
- Pressure swing adsorption: Biogas is pressurized and carbon dioxide adsorbed by a material. By subsequently decreasing the pressure the carbon dioxide is released.
- Water and organic physical scrubbers: More carbon dioxide than methane will dissolve in water. The carbon dioxide that is dissolved will be transported away by the water, leaving a methane rich gas. Organic physical scrubbers work on the same principle as water scrubbers, but utilize an organic solvent rather than water.

A number of national standards exist that consider various aspects of biogas and fossil gas use, in order to assure that the upgraded gas is of good enough quality to assure smooth operation. These standards tend to cover both biogas and fossil gas, in order allow substitution. As the composition of fossil gas depends on its source the standards will vary in accordance to the source composition of the natural gas.

In Sweden a national standard exists for biogas as a fuel for Otto engines, SS 15 54 38. It is currently the only standard available for biogas used as a vehicle fuel. It is in need to be updated. The update is handled through the committee "SIS/TK415 Motorbränsle" and the work group "AG5 Naturgas och Biogas".

Diesel engines dominate off-road applications due to their high efficiency. It would hence be advantageous to use biogas in Diesel engines. However, there are numerous differences between Diesel and biogas. Most importantly, Diesel will ignite in a Diesel engine, whilst biogas will not. In order to run a Diesel engine on biogas Diesel has to be used as a pilot fuel to initiate combustion, whilst biogas can be supplied later to contribute most of the energy. An engine that uses biogas and Diesel in a Diesel engine is called a dual fuel engine. Such an engine would is expected to have an efficiency between that of Otto engines and Diesel engines fuelled by Diesel (Königsson, 2012). Dual fuel engines have been the subject of a number of studies. Sahoo et al (2009) have published a review for natural gas/biogas, whilst Abd Alla et al (2002) have produced one for similar LPG fuels.

The burn rate of methane is lower than for Diesel (Badr et al, 1999, Abd Alla et al, 2002). It will hence need more time to burn, with more of the combustion taking place after the top dead centre (when the piston is already moving downwards). Further, the engine has to be throttled in order to keep the equivalence ratio close enough to stoichiometric to assure good flame propagation. As a consequence the thermal efficiency will tend to be lower than for Diesel (Badr, Karim, & Liu, 1999; Königsson, 2012) and decrease with increasing biogas share (Abd Alla et al, 2002). This effect is likely to be strengthened with more CO_2 in the gas. With an increased pilot quantity the combustion process is assisted by a greater energy release on ignition and a larger Diesel plume than supports more early ignition centres and heat transfer to the biogas (Badr et al, 1999; Königsson, 2012). When the size of the pilot injection is increased past that needed for complete combustion (i.e. the flame(s) propagating successfully through the cylinder) the impact on CO and unconverted methane is limited (Badr et al, 1999).

Emissions from Dual fuel operation can be expected to differ from emissions during Diesel operation. Broadly speaking CO can arise from either a lack of oxygen or time. The amount of CO in the exhaust tends to be higher with dual fuel than with just Diesel at all loads (Badr et al, 1999; Uma et al, 2004; Yoon, 2011; Karim, 2015). At low loads the CO concentration increases with gas share. As the load increases the concentration reaches a peak at progressively lower gas shares (Papagiannakis & Hountalas, 2003); likely due to incomplete combustion. In Dual fuel mode CO emissions are at a minimum at slightly oxygen rich mixtures, whilst with Diesel it continues to decrease with even very oxygen rich mixtures (Königsson, 2012). Emission of NO_X is mainly influenced by cylinder temperature and access to oxygen. It increases with load, due to higher cylinder temperatures. Due to decreased cylinder temperature it decreases with increased gas share at all loads. Increased pilot fuel quantity increases emissions (Papagiannakis & Hountalas, 2003; Sahoo et al, 2009; Yoon, 2011; Karim, 2015). HC emissions are in the case of dual fuel engines associated with unburned methane escaping the engine cylinder. Emissions are highest at low loads. They are substantially higher than with pure Diesel, due to the unburned methane (Badr et al, 1999; Papagiannakis & Hountalas, 2003; Yoon, 2011; Königsson, 2012; Karim, 2015). Soot concentrations increases with load. They are substantially lower in dual fuel mode than in Diesel mode (Yoon, 2011). At low loads soot concentrations decreases linearly with methane content, at high loads the relationship is more convex (Papagiannakis &

Hountalas, 2003).

As inert CO_2 replaces CH_4 the combustion temperature is reduced and as a consequence less NO_X is formed. Bari (1996) mixed natural gas with carbon dioxide to study its impact. The CO_2 share of the gas was increased from 0 up to 40 % and the Diesel substation rate varied between 15 and 75 %. In general the gas flow was increased as the CO_2 share is increased, but not enough to assure an unchanged methane flow, rather the size of the Diesel pilot injection was increased somewhat. His study showed that the impact of CO_2 on fuel consumption was small and that it was at its lowest at about 20-30 % CO_2. Bari suggested that this was due to CO2 dissociating into CO and O_2, as the flame temperature is high enough to initiate dissociation. These products will work as a catalyst for the combustion process, increasing the total burn rate (Balleny, 1986, Bari, 1996). However, when the CO_2 share increased over 40 % the engine began to run harshly.

Henham & Makkar (1998) mixed natural gas (94 % CH_4) with CO_2 at various Diesel substitution levels. They found that the overall efficiency fell with increasing CO_2 at all constant levels, though the impact was limited at low levels of gas mixture. They studied CO emissions, but found them to be mainly influenced by the Diesel substation levels and not the CO_2 share; and attributed these changes to changes in the effective air-fuel ratio.

Jawurek (1990) studied the impact of changed CO_2 share on SI-engines. He found that an increased CO_2 share led to less power, poorer combustion and harsh running and that these changes could be counteracted by supplying petrol. It should be born in mind that the consequences of increased CO_2 will depend on the engine control strategies. If other control strategies than those used in the mentioned studies are used the results can be different.

Experiments using cold EGR, can be expected to have a similar impact, as the extra charge in both cases are cold and do not supply any extra chemical energy. Increasing the amount of CO_2 in the gas is similar to increasing the exhaust gas recirculation (EGR). Paykani et al (2012) showed that increased EGR decreased efficiency (at low loads and high gas shares).

3. Method

3.1. System analysis

In order to model the impact of changed biogas purity a number of system parameters for the biogas plant, biogas vehicles and for the economy had to be considered. The parameters for the plant were: production capacity, CH_4-concentration in the raw biogas, life span and maintenance cost. For the vehicle the gas pressure and storage capacity and the number of vehicles was considered.

For interactions with the wider society the alternative use of the raw biogas and the upgraded biogas was considered (with regards to value of the gas and emissions). The economic parameters were: interest rate, labour, (electrical) energy use, Diesel costs and the cost of buying and selling biogas.

The gas used in the tractors could either have a farm origin or be bought at a market (and as a consequence be either fossil natural gas or renewable biogas). The raw biogas was assumed be used in a CHP if not upgraded. It would hence have an economical value corresponding to the value of the heat and electricity produced in a CHP and emissions typical of its use in CHPs.

Three different gas qualities were considered: 65 % (raw biogas), 80-96 % (upgraded biogas) and 96 % (bought gas). If the gas was upgraded it was assumed that it was used locally as it was assumed that the demand for gas upgraded to less than 96 % would be low as it cannot be used in road vehicles.

It was assumed that the tractor ran on biogas until the tank was empty, after which it was switched to run solely on Diesel for the rest of the day. This was based on experience from practical use (Lindvall, 2015). Any refuelling during the day would take such long time that it would not allow normal farm operation.

It was assumed that the farm used a high number of tractors (either their own or other farmers through some mutual agreement). The assumption was motivated by necessity to have enough demand for the gas in order to have any hope of having a cost effective system.

The economic and environmental utility of using low methane biogas was compared with conventional tractors, run on bought Diesel. For the standard scenario the parameter values listed in Table 1 were used.

Table 1 Parameters used for the standard scenario

Parameter	Value	Unit
Production		
Production	19	Nm^3 biogas/h
CH_4-purity (in)	65	%
Tractor		
No. of tractors,	15	-
Storage, pressure	200	bar
Storage, volume	170	l
Max velocity	40	km/h
Economy		
Cost, labour	300	SEK/h
Cost, energy	0.40	SEK/kWh
Interest	8	%
Biogas, cost buying	1.10	SEK/kWh
Diesel, cost buying	1.30	SEK/kWh
Feed stock cost	0.20	SEK/kWh
Use		
Working hours/day	8	h/day
Consumption, summer share	70	%
Maintenance cost, upgrading		
Upgrading, life span, t_{upg}	10-20	Years

Power consumption	(see Lindgren, 2007)	%/mode
Compressor		
Capacity	50	Nm^3/h
Cost	50,000	SEK
Society		
Thermal efficiency, other use	30	%
Thermal efficiency, other production	90	%
Emissions, CO_2, other use of raw gas	40	g/kWh[1]
Emissions, CO_2, other use of upgraded gas	180	g/kWh [2]
Emissions, CH_4, other use	0.41	g/kWh
Emissions, CO_2, electricity production	40	g/kWh

3.2. Engine tests

Tests were performed on a Valtra N123 tractor with an AGCO Power 44AW engine in a test bench. The tractor was not adapted to the lower methane content. The lower methane content was handled by its existing engine control unit. The engine had an unmodified common rail Diesel injection system whilst the gas was injected in the intake. A low pressure circuit with a pressure regulator reduced the gas pressure to about 0.35 MPa. An injector package from Bosch was used to mix the gas with the air in the inlet. An Ecocat catalytic converter that converts methane and other hydrocarbons to CO2 and H2O was added to the exhaust system, which was otherwise unchanged compared to the original Diesel only system.

Fuel consumption was measured gravitationally using a K2660824 load cell. Load was measured by a Froude Consine AG400 HS dynamometer, controlled by a Froude Texcel V4. The engine remained seated in the tractor and the dynamometer was connected to the power take-off. Therefore the produced power was the net power, omitting the power needed for transmission and support systems (cooling fan, generator etc.).

Emissions were measured on undiluted gas. CO and CO_2 were measured on dry gas, the other pollutants on wet gas. CO and CO_2 were measured using nondispersive infrared sensors. HC and CH_4 were measured using a flame ionization detector. Particulate emissions were measured by a PPM-M sensor. Emissions were measured in accordance with directive 97/68/EG (incl. 2010/26/EG) on five gas mixtures ISO8178. The mixtures were produced by diluting conventional, traded biogas gas.

Two test series, with different load patterns, were used to test the tractor in the test bench. In the first series only the non-road transient cycle was used. It was used for five different mixture compositions (85%, 88%, 90%, 94% and 97 % CH_4), but not pure Diesel. In the second series both the non-road stationary and the non-road transient cycles were used. Only two different mixture compositions were used (85 %, “low” and 97 %, “high”).

[1] Energy of fuel, not useful energy out of a heat engine
[2] Energy of fuel, not useful energy out of a heat engine

4. Discussion

It is almost always environmentally advantageous to upgrade. The two exceptions are if few tractors are used (so that the upgraded gas would have very little use) or if raw biogas is supposed to replace a fossil fuel with high net CO_2-emissions. That is if for example the farm would use a fossil fuel for heating in the absence of biogas. However, in order for this potential advantage to be of practical interest it also have to be economically advantageous to upgrade and here the picture is less clear.

In the standard scenario it was not profitable to upgrade, the loss being at least 200,000 SEK/year. Whether it is economically advantageous to upgrade or not depends on several factors, of which some are rather uncertain. One such factor is the loss of efficiency if a dual fuel engine runs on biogas with a lower than usual methane content. The engine studies were, as described below, somewhat inconclusive. Steady state measurements showed that such a loss existed, whilst transient measurements showed no such loss. The, still rather limited, literature is also rather unclear on this important issue. If the loss calculated from the steady state measurements are used the conditions under which it is more profitable to produce fuel quality biogas rather than run on Diesel is fairly limited, requiring conditions that makes biogas much more economically attractive than is currently the case, for example by increasing the cost of Diesel. If there is no such loss it becomes, however, more profitable to use biogas.

The environmentally optimal methane content tends to be as high as possible or close to as high as possible, as the environmental cost of upgrading is low whilst the benefit of replacing Diesel with biogas is high. However, the economically optimal methane content varies substantially depending on the assumptions used. Using the engine loss measured from steady state measurements on the engine the optimal methane content is 92 % at standard conditions. If it, however, is assumed that there is no engine loss the optimal methane content drops to 84 %. The reason for the lower share is that the drawback of using low methane contents is reduced due to the absence of any loss, whilst the benefit in form of cheaper upgrading still exists. If the cost of upgrading can be reduced the optimal methane content will increase.

In Table 2 the conditions under which it is advantages to upgrade is compared for two different alternatives. The first one uses the standard conditions used for the rest of the report, the second one assumes that there is no loss of efficiency.

Table 2 Conditions under which it is advantageous to upgrade, with varying assumptions regarding loss of efficiency with low methane content.

Variable	Loss of efficiency based on steady state measurements		No loss of efficiency	
	Economy	Emissions	Economy	Emissions
Engine loss of efficiency	Never	Always	-	-
Production volume	Never	Always	Never	Always
Number of tractors	Never	>7(.2)	Never	>5
Raw gas quality	Never	Always	Never	Always
Raw biogas value	<0 SEK/kWh	Always	<0.11 SEK/kWh	Always
Diesel value	>1.44 SEK/kWh	Always	>1.35 SEK/kWh	Always
Fuel tank size	>266 l	Always	>207 l	Always

Rent	<1.77 %	Always	<3.63 %	Always
CO_2 from replaced fuel	Never	<335 g/kWh	Never	<335 g/kWh
CO_2 from electricity	Never	Always	Never	Always
Optimal fuel quality at standard conditions	92 %	96 %	84 %	95 %

4.1. Economy

The economically optimal gas quality is typically slightly lower than the current one. Compared with Diesel it is, with current technology, difficult to achieve improved economy by using biogas. In order to do so would in general require either technological progress on multiple fronts or changed economic conditions that makes upgrading more profitable (such as a higher Diesel cost).

In general conditions under which purities substantially lower than the current one becomes optimal are also conditions under which economic conditions are tougher. Whilst it might be preferable to have lower concentrations if the number of tractors is low or the Diesel price is low it is also unlikely that it will be economically advantageous to build an upgrading unit at all under such conditions. An important exception to the prior comment is if the loss of efficiency of using less purified Diesel can be reduced. In such case the optimal methane concentration decreases fairly rapidly.

The variables that have the biggest impact on profitability are the fuel costs and the vehicle tank size. The economic benefit of using biogas to the farmer is that it replaces costly Diesel. If the price of Diesel increases it hence becomes more interesting to upgrading to higher concentration, if it decreases it becomes less interesting to upgrade. Larger fuel tank volumes will improve both the economic and the environmental impact substantially; it will however have a very limited impact on the optimal purity.

4.2. Environment

The environmentally optimal gas quality is the current one except if the raw biogas is assumed to replace some carbon intense fuel. The optimal methane content is usually not sensitive to changes in various variables as the advantage of replacing Diesel with biogas is a very substantial one and hard to offset by other changes.

The variables that have the biggest impact on environmental benefit are the emissions of the fuel that biogas replaces as well as the number of tractors used and the size of their fuel tanks. The environmental benefit increases rapidly with more tractors. Larger fuel tank volumes will improve both the economic and the environmental impact substantially; it will however have a very limited impact on the optimal purity. If the raw biogas is assumed to replace a fuel with emissions approaching or surpassing that from Diesel in engines (700 g/kWh) the net benefit of upgrading disappears. The impact of CO_2 emissions from electricity is comparatively small. A change from 0 to 1,000 g/kWh electricity increases emissions with 60 g/kWh biogas.

4.3. Engine studies

Engine studies were performed using both the non-road stationary and the non-road transient cycles. The stationary and transient cycles operate at slightly different conditions and hence the influence of fuel quality on emissions can be expected to differ simply due to the different conditions. Different results between the stationary and transient cycles can hence be due to both different average conditions and due to transient effects in the transient cycle. The stationary cycle has a mean torque of about 330 Nm and a mean engine speed of 1,650 rpm and a mean power of 57 kW. The transient cycle on the other hand has a mean torque of 157 Nm and a mean engine speed of 1,750 rpm and a mean power of 30 kW. It was therefore to be expected that transient measurements will show results that will be more weighted by conditions at low loads. Not only do the mean properties of the cycles differ. The transient cycle operate over a wide range of torques and speeds, whilst the stationary cycle on cover eight torque/speed combinations. A comparison of the results with the various test series is shown in Table 3.

Table 3 Emissions with “low” for the different tests

Emissions	CO	CO_2	NO_X	THC	CH_4	PM (mg)	Power	Efficiency
Transient 1	0.32	1,002	5.26	0.92	1.18	146.70	30.6	19.0%
Transient 2	0.18	1,013	5.93	0.99	1.43	3	30.4	16.8%
Stationary 2	0.09	844	4.94	1.84	2.15	4	57.8	24.9%

Still, many trends were apparent in both the stationary and transient cycles, as shown by Table 4. Emissions of CO_2 were highest with low methane contents. However, the trend was much more pronounced in the second set of tests. Emissions of pollutants produced under rich conditions decreased with low methane contents. In this case the trend was strongest in the first set of tests. Emissions of unburned hydrocarbons, including methane, showed a U-shaped trend in the first transient tests. However, again, the trend was much weaker in the second set of tests.

Table 4 Emission with a stated methane share/emission with 86.3 % methane (both measured in g/kWh)

Emission	CO	CO_2	NO_X	THC	CH_4	PM	Power	Efficiency
Transient2, 95.0 %	101.4	93.2%	103.5%	100.5%	99.1%	5	100.6%	107.7%
Stationary, 95.0 %	100.6	94.6%	114.3%	95.4%	97.8%	6	98.6%	102.9%
Transient1, 97.6 %	119.2	98.7%	119.4%	102.0%	102.4%	168.8	100.1%	99.7%
Transient1, 96.0 %	111.9	97.8%	113.9%	86.6%	87.1%	152.4	100.3%	99.0%
Transient1, 92.0 %	104.1	98.5%	108.2%	74.4%	76.9%	135.3	100.2%	99.9%
Transient1, 87.6 %	102.7	99.3%	104.6%	81.1%	82.4%	125.3	100.1%	102.9%
Transient1, 86.3 %	100.0	100.0%	100.0%	100.0%	100.0%	100.0	100.0%	100.0%

The results were consistent in terms of average emissions. Emissions of CO and NO_X decreased, so that the value at “low” (86.3 % methane content) was about 85 % of the values at “high” (95-97 % methane content). Emissions of particulates decreased even further, the values at “low” being 50-60 % of those at “high”. The decrease as a function of methane content was close to linear for CO, NO_X and particulates. The emissions of hydrocarbons in general and methane in particular was similar at “low” and “high”. However, an analysis of the first transient test series revealed that these emissions were not linearly dependent on methane content and had their lowest values at a methane content of 90 %.

The impact of methane content on engine efficiency was less clear. Steady state measurements indicated that the efficiency decreased with decreasing methane content, so that the efficiency at “low” was about 96-97% of that at “high”, for the transient measurements no such trend could be found.

The tractor engine was able to produce the same torque, speed and power at all methane contents. It is therefore to be expected that tractors running on biogas with less methane will not differ from tractors running on 96 % methane whilst performing field operations.

4.4. Other aspects

Ongoing work on future standards on a component basis

The Swedish biogas standard for Otto engines, SS 15 54 38, considers vehicles with ("B") and without ("A") lambda sensors. Whilst the methane level should be about 97 % in both cases it is allowed to differ by 2 % if lambda sensors are used, whilst it is only allowed to differ by 1 % in the absence of sensors. The standard will be updated through the committee "SIS/TK415 Motorbränsle" and the work group "AG5 Naturgas och Biogas". There is a small, but potentially increasing, interest for vehicles that run on a lower methane level. It is mainly farms and small distributors that would be interested in lower levels. The work group suggests that such gas would not be allowed to be distributed at public fuel stations (Svensson, 2011). Most involved actors were against establishing a standard that would allow for gas with a lower, more fluctuating, methane content to be used for local consumption; though several actors considered the question to be outside their area.

The work group suggested that gas sold publicly should have a minimum methane level of 95 %, whilst local/non-public gas should have a minimum level of at least 86 % (the same concentration as G25, a natural gas reference fuel). Requirement of a minimum heating value at the national level may in the future come into conflict with planned regulation at European level. The ongoing regulatory process at European level currently only considers the H-gas, with a lower limit corresponding to a 92.5% methane content (EC 2007).

Impact of other fuel components

This section provide an overview of the impact of most commonly considered contaminants on the biogas system and to which degree their concentration might be affected by less purification. **Ammonia** is usually separated when the gas is dried or when it is purified. Normal upgrading effectively removes ammonia down to very low levels. **Hydrogen sulphide** is removed by processes that are mostly separate from CO_2 removal, changing the allowed methane content will therefore in general not have an impact on hydrogen sulphide levels. **Oxygen** and **nitrogen** are, if available in the raw gas, removed by adsorption with activated carbon, molecular sieves or membranes. The impact of changed upgrading is hence likely to in general be small, but dependent on upgrading technology. No technology removes nitrogen; hence it will not be influenced by a changed methane content. Changed upgrading will not have any impact on the **sulphur** from odorization as it is added afterwards. **Particulates** are removed by mechanical filters and hence not affected by upgrading choices. Minute amounts of lubricating oil and hydraulic oil enter the gas stream during compression. It is hence unlikely to be influenced by a changed methane content.

Impact of changed methane content on other upgrading technologies

With regards to PSA most adsorbents are considerably more selective (i.e. adsorbing CO_2 at a much higher rate than CH_4) at lower pressures than at higher pressures. If a higher CO_2 share is accepted it would be possible to increase the capacity by working at a higher pressure, as the lower selectivity would be acceptable. Further, if the allowed methane content is changed it might allow the use of adsorbents that might be cheaper, but less selective, than the ones currently used. On the other hand for amines, as long as normal operating conditions such as enough amines being available apply, amine scrubbers produce a gas of a very high purity. It is therefore unlikely that allowing for higher CO_2 concentrations would lead to cheaper upgrading.

Membrane upgrading

During the duration of the project a Master student expressed interest in the project. This allowed a wider study of options to offset biogas using membrane technology. This section contains a summary of the work, for a full coverage read the thesis: *Small-scale Biogas Upgrading with Membranes: A Farm- Based Focused Techno-Economic and Social Assessment for Sustainable Development (Mamone, 2014).*

Based on semi-structured interviews conducted with relevant representatives and experts dealing with farm-based biogas upgrading systems and innovations the following factors were considered important with regards to membrane upgrading technology:

- Experience with the technology/proof of principle
- Availability of trustable information, in particular for very new technologies
- Maintenance is a big issue. Farmers want the plant to run with relative ease. The farmer is a food producer mainly. Biogas is not the main subject.
- In general the market is a major issue. Will anyone buy the gas? One of the main reasons for producing vehicle fuel is to create a stable market. Heat and electricity solely do not allow for this.
- One of the most common problems is downsizing the technique. A big problem is that most upgrading plants are too big, and if you downsize them to fit to a farm, it is too expensive.

5. Conclusions

Engine tests showed that the engine could cope well with changes in methane content. It could produce the same speed, torque and power independent of the methane content. Emissions were in general lower when biogas with a lower methane content was used. The impact of engine efficiency was less clear, with the results depending on the used test cycle. Considering that the engine is under development and that other manufacturers might make different design choices the results should be considered no more than an indication of what can be expected with a lower methane content.

On a systems level there is little environmental reason to use a lower methane content, as less Diesel will be replaced and the environmental benefit of replacing Diesel is very substantial. In general there is little economical reason to use a lower methane content, as the conditions at which it is more advantageous to have a lower methane content is also conditions for which the overall economy of biogas upgrading is bleak. However, the picture might change if there is no loss of efficiency with a low methane content.