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Energy balance and global warming potential of biogas-based fuels from a life cycle perspective

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ABSTRACT

Biogas is a multifunctional energy carrier currently used for co-generation or compressed biomethane as vehicle fuel. Gas-to-liquid (GTL) technology enables conversion of biogas into other energy carriers with higher energy density, facilitating fuel distribution.

The energy efficiency and global warming potential (GWP) for conversion of biogas to compressed biogas (CBG), liquefied biogas (LBG), Fischer–Tropsch diesel (FTD), methanol and dimethyl ether (DME) were studied in a life cycle perspective covering the technical system from raw biogas to use in city buses.

CBG, methanol and DME showed the best specific fuel productivity. However, when fuel distribution distances were longer, DME, LBG and methanol showed the best energy balance. Methanol, FTD and DME emitted half the GWP of LBG and CBG. Choice of electricity mix had a large impact on GWP performance. Overall, taking into account the different impact categories, combustion properties and fuel yield from raw biogas, DME showed the best performance of the fuel conversion scenarios assessed.

1. Introduction

Fossil fuels currently comprise 80% of global primary energy consumption, 58% of which is consumed by the transport sector alone [1]. Biofuels are renewable alternatives and, owing to their origins in natural bioresources, they are geographically more evenly distributed than fossil fuels. Biogas (approximately 60% methane (CH_4), 40% carbon dioxide (CO_2) and some trace gases) produced during anaerobic digestion of organic matter (organic waste, sewage, manure etc.) is a renewable energy carrier, which can be used for e.g. combined heat and power (CHP) production. However, if biogas is cleaned and upgraded in order to increase the energy content, the resulting biomethane can be used as a renewable substitute for natural gas. By the end of 2012, 221 biogas upgrading plants were in operation worldwide, of which 55 units were located in Sweden. Water scrubbing, pressure swing adsorption and chemical scrubbing are the choice of technology in 90% of these plants [2]. The biomethane is uploaded to the natural gas grid or directly compressed to CBG (compressed biogas) for vehicle use.

Due to the limits of grid infrastructure in certain regions and problems relating to storage and distribution systems for CBG, interest in technologies which convert biomethane to even higher energy density and more feasible transportability has increased. The option of converting biomethane to liquid biofuels would facilitate the supply of biofuels to geographically broader and larger markets. Furthermore, the potential for blending with liquid fossil fuels would be very useful. Today there are different routes for exploiting biogas energy as liquid biofuel. Liquefied biogas (LBG) is a form of upgraded biogas that has been cooled and liquefied at temperatures around −161 °C under atmospheric pressure by cryogenic technology. LBG is three times more space-efficient than CBG (stored at 200 bar), while the fuel is in the gas phase when it reaches the engine [3].

A novel route of biogas conversion to vehicle fuel is gas-to-liquid (GTL) technology, a means to exploit gaseous energy sources as fuel, higher hydrocarbons (e.g. ethylene, a-olefins, paraffin, wax) and chemical products [4,5]. Existing GTL technology includes conversion of methane (from natural gas or upgraded biogas) to syngas (a mixture of carbon monoxide (CO) and hydrogen gas (H_2)) and subsequent synthesis to e.g. Fischer–Tropsch Diesel (FTD), methanol and dimethyl ether (DME) through catalytic synthesis. Interest in producing GTL fuels from biomass and biogas as available renewable feedstock is increasing [6,7]. Moreover, the current situation of high oil prices and anticipation of increased market share for diesel fuels presents an entry point for GTL alternatives to the biofuel market.

FTD is interchangeable with conventional diesel fuels and fully compatible with existing diesel engines and infrastructure, which is conducive to implementation in the short term [8]. FTD has a high cetane number, does not contain sulphur or nitrogen and has the potential for blending with diesel at any ratio with little to no modification of diesel engines [4]. In addition, synthetic fuels have emissions benefits in the reduction of hydrocarbons (HC), CO, nitrous oxides (NO_x) and particulate matter (PM). Synthetic fuels can satisfy many of the ideal fuel requirements of modern diesel engines [9].

Methanol is another GTL product, which has been produced for many decades for manufacturing of high-value chemicals and fuel

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additives. Methanol is the most basic alcohol and is a desirable choice as a transportation fuel due to its efficient combustion and ease of distribution. Methanol can be used directly as fuel or blended with petrol, converted to DME as a diesel replacement, or used in the biodiesel production process [10–12]. Methanol is a high-octane fuel that enables very efficient and powerful engine performance. However, methanol is toxic, has an affinity to water and has half the energy content of petrol on a volumetric basis [13]. Since methanol fuel is corrosive to certain materials commonly used in engines and fuel lines, it is blended with other fuel. Small modifications must be made to engines to include methanol-compatible components and to permit running on high-level blends such as M-85 (a mixture of 85% methanol and 15% petrol). However, low-level blends of methanol do not cause adverse effects on car engines and can be used in cars today where available without any problems. Methanol is indeed also considered an alternative to marine gas oil or liquefied natural gas for ship propulsion and is claimed to have advantages in this application [14]. However, the substitution of marine gas oil with methanol is not within the scope of this paper.

DME is the simplest ether primarily produced directly from syngas or indirectly by dehydration of methanol. Due to the chemical structure of DME, the possibility of forming carbonaceous PM and NO_x emissions during combustion is limited [15]. DME combustion does not produce soot and is considered a clean fuel. Unlike methanol, DME is a gas at ambient temperature and pressure, so it is stored under pressure as a liquid similar to liquefied petroleum gas (LPG) and can use the same existing infrastructure as LPG [16]. The most challenging aspects of a DME engine relate to its physical properties and not its combustion characteristics. A DME fuel storage tank must be twice the size of a conventional diesel fuel tank due to the lower energy density of DME compared with diesel fuel, in order to achieve an equivalent driving range to CIDI (Compression-Ignition Direct-Injection) diesel. Modifications to pumps and fuel injectors are needed due to the 20-fold lower viscosity of DME compared with diesel [17].

Today, innovations in GTL technology, e.g. micro-channel technology, have led to improvements in efficiency of productivity and infrastructure. Introduction of the micro-channel technology will enable transformation of energy and chemical processing industries by greatly reducing the size of chemical reactor hardware. The main characteristic of micro-channel technology is parallel arrays of micro-channels, with typical diameter dimensions in the 0.1–5.0 mm range. Processes are accelerated by reducing heat and mass transfer distance, whereby system volumes can be reduced 10-fold or more compared with the conventional hardware [18–20].

Thus, the development of small-scale GTL technology offers future possibilities for converting biogas from anaerobic digestion to liquid fuels, facilitating distribution and flexible use. However, when nominating novel systems there is a need to analyse the energetic and environmental performance in a systems perspective and to compare it with that of conventional techniques. Life cycle assessment (LCA) is an internationally accepted method for measuring environmental performance and a useful tool for analysing products or services. LCA enhances the understanding of how alternative systems compare with each other, but also how different sub-processes in a system affect the overall results [21]. LCA methodology aims at change, or improvement: sometimes in more direct ways (decision-making) and sometimes in more indirect ways (influencing market behaviour, identifying improvement possibilities) [22].

Reduction of greenhouse gas (GHG) emissions is one of the main reasons behind introducing biofuels as alternatives to fossil fuels. In order to ensure that these GHG emissions are not excessive, emission limits and methods for calculating the emissions have been introduced into biofuel standards and legislation. In 2009, the European Union introduced sustainability criteria for biofuels in two directives; the Renewable Energy Directive (Directive 2009/28/EC) [23] and the Fuel Quality Directive (Directive 2009/30/EC) [24]. In these sustainability criteria a methodology to account for GHG savings compared to fossil fuels is described. The sustainability criteria have greatly influenced the biofuel producers and the biofuel market in the EU.

The objective of this study was to assess alternative biogas processing routes in terms of their energy efficiency and global warming potential (GWP) in a life cycle perspective. The study included conversion to liquid and gaseous fuels, such as LBG, FTD, DME and methanol, as well as conventional conversion to CBG. The assessment covered the technical system from raw biogas to use of the biofuel in public city buses.

2. Methodology

The energy and environmental performance of the biofuel production chain, including raw biogas upgrading, fuel production, storage, distribution, fuelling and final conversion in bus engines was included in the study. The study was based on the LCA methodology described in ISO standards 14040 and 14044 [25,26], however some important deviations from the standards were made; the assessment was limited to only two impact categories and only energy allocation was included. This is similar to the methodology described in the sustainability criteria for biofuels in the EU [23]. Further the study had an attributional modelling approach, i.e. accounts for the immediate physical flows in a life cycle. This can be compared to consequential LCA-modelling, which examines the environmental consequences of change in a life cycle, often with a market-oriented approach [27].

The energy performance was based on the energy output (LHV; lower heating value) of the biofuel produced, compared to the required primary energy (PE) input. Factors used for conversion of data on electricity, heat and diesel to PE are presented in Table 1. The PE factor is defined as the ratio between PE and delivered useful energy. Included in PE are extraction of fuel, transportation and conversion, transmission and distribution losses [3].

The environmental impact included was GWP considering the direct emissions of the greenhouse gases CO_2, CH_4 and N_2O during the life cycle of biofuel production. Direct emissions were defined as emissions occurring inside the system boundary, connected to the fuel production chain, an example being emissions from production of input electricity. Emissions occurring outside the system boundary, such as emissions occurring from market induced changes, were not included in this study. The emissions were calculated as CO_2-equivalents (CO_2-eq.) using characterisation factors for a 100-year perspective based on IPCC, 2007 [28]. According to this, 1 kg of CO_2, CH_4 and N_2O is weighted as 1, 25 and 298 kg CO_2-eq., respectively. Biogenic carbon was not included in the GHG accounting.

In the GTL scenarios (FTD, methanol and DME), fuel synthesis was modelled in flow sheet software (AspenTech's Aspen Plus 7.3.2). The simulations performed are applicable to the micro-channel concept described above. The operating parameters used for the unit operations are summarised in Appendix A.

2.1. Functional unit and system boundaries

A common basis for calculation had to be defined in order to compare different scenarios. Each scenario was analysed based on energy balances and GHG emissions. Since the aim of this study was to assess alternative processing routes for raw biogas, an input-based functional unit (FU) was deemed appropriate. Thus, the FU was defined as 1 Nm^3

Table 1
Primary energy (PE) factors for different energy carriers (MJ PE/MJ energy carrier).

Energy carrier	Specifications	Primary energy factor
Electricity	NORDEL	2.17[a]
Fuel	Diesel, low-sulphur	1.27[a]
Heat	District heating	0.79[b]

[a] [24].

[b] [25].