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Biomethane in the transport sector—An appraisal of the forgotten option

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ABSTRACT

The last 20 years efforts to find a long-term and large-scale biofuel alternative to petrol and diesel for the transport sector have been intensified with a focus on liquid biofuels, such as ethanol, methanol and Fischer–Tropsh diesel derived from wood. The large-scale production of biomethane has so far largely been overlooked in comparative studies that focus on the long-term renewable options. The aim of this article fills this gap and to provide a broad and systematic assessment of the future potential of biomethane compared to other biofuels. In order to become a large-scale option, biomethane production from woody biomass via gasification needs to be developed and commercialized. However, biomethane exhibits a clear development path with relatively low financial and technical risks starting with local solutions utilizing wet biomass resources towards medium and eventually large-scale gasification with economics similar to liquid second generation biofuels. The disadvantage of being a gaseous fuel is not insurmountable and can furthermore be relaxed by the integration and dual-use of the existing distribution system for natural gas. This assessment concludes that more emphasize should be given to biomethane as a large-scale option given the opportunity to use woody biomass from gasification.

1. Introduction

The transport sector is almost completely dependent on fossil fuels, >96% globally (IEA, 2007). High oil prices, increasing concerns for energy security, air quality problems and the need to drastically reduce the emissions of greenhouse gases are some of the great challenges facing the transport sector today. Since the early 1990s the debate and the efforts to find efficient and renewable alternatives to the internal combustion engine—petrol/diesel nexus have been intensified.

The policy landscape for alternative transport fuels are changing rapidly and have certainly not come to any conclusion yet but it seems unlikely that we will see a similar dominance of one specific feedstock (crude oil) in the future as we have witnessed the last 100 years. The introduction of liquid biofuels (ethanol and biodiesel) has resulted in a rapid growth the last four years. However, the sustainability of the current and planned expansion of ethanol and biodiesel production is put to question. What is clear is that the current production of ethanol and biodiesel from agricultural feedstocks cannot grow too much or too fast before being constrained either by economical, for social or for ecological reasons, see Börjesson et al. (2009) for an extensive overview.

In order to minimize the pressure and completion for scarce land resources, the development focus for biofuels is now focussing on utilizing woody biomass, so called "second generation" of biofuels. This can be done either via enzymatic hydrolysis or via gasification. Other long-term and strategic research efforts have targeted "grand" solutions with the potential for a complete transformation of the current fossil fuel-combustion engine nexus and a complete decarbonisation of the entire transport sector. Examples are the US Freedom Car project and the Japanese "fuel-cell vision".[1] These long-term efforts include zero-carbon energy carriers such as electricity and hydrogen that requires a completely new fuel infrastructure and rapid technology development of batteries and/or fuel cells.

This paper focuses on biomethane as a renewable fuel option. Currently, biomethane is a local and small-scale option mostly produced by upgrading biogas from locally collected wet biowaste. Biomethane is also produced from dedicated agricultural crops (grasses and maize) which has a larger potential but is still limited by competition for land suitable for other purposes such as food. In order to become a large-scale option, biomethane produced from woody biomass via gasification and methanisation needs to be developed.

Lately there has been a growing interest for biomethane from gasification of woody biomass in the academic literature.

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[1] See e.g. NRC (2005) for "Freedom car project" and METI (2001) and METI (2008) for Japanese fuel-cell visions.

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Mozafarian et al. (2004) and Zwart et al. (2006) analyzed the technical and economic potential to replace natural gas with biosynthetic natural gas (SNG) in the Netherlands, Seiffert et al. (2009) in Chile, Ramesohl and Stucki (2007) and SGC (2008) have provided the technical and economic arguments for expanded use of biomethane, Åhman et al. (2005) analyzed biomethane as an intermediate solution towards zero-carbon transport sector and finally Schultz et al. (2007) analyzed biomethane in the Swiss transport sectors using a Markal-model with competing uses of woody biomass for heating and electricity.

However, despite this, the large-scale use of biomethane has largely been overlooked in previous major comparative studies that focus on the long-term and large-scale options for the transport sector, see e.g. Concawe et al. (2007), IEA (1999, 2004), MacLean and Lave (2003), IPCC (2007), WEA (2000), Faaij (2006).

The aim of this article is to fill this gap and to provide a broad and systematic assessment of the future potential of methane as a fuel for road transport compared to other biofuels. For this purpose we (i) describe biomass to methane conversion routes, (ii) review the short- and long-term economic prospects, (iii) discuss the alternative uses of biomethane in a climate restricted world and the link to natural gas, (iv) assess the development needs and barriers for biomethane compared to the other alternative biofuels. The article takes an EU perspective with examples from the EU.

2. Conversion technologies for biomethane

Biomethane denotes here a gaseous fuel consisting of $>97\%$ methane of biological origin that is fully compatible with existing compressed natural gas (CNG) vehicle systems and fulfils the quality demands for injection into the natural gas grid. Biomethane can be supplied both by upgrading biogas (consisting of 45% to 65% methane) derived from digesting wet biomass and by gasifying of woody biomass followed by a methanisation step.

2.1. Utilizing wet biomass

Biomethane today is produced by anaerobic digestion of wet biomass (manure, household waste). Anaerobic digestion is a biological process in which organic materials are converted to biogas in the absence of oxygen. The digester produces biogas containing approximately 45–65% methane and the rest mainly being CO_2. In order to be suitable for vehicle use or for injection into the natural gas pipe-lines the biogas must be dried, cleaned and upgraded to meet pipe-line specifications. In the cleaning process trace component such as hydrogen and sulphideare removed. In the upgrading process, the carbon dioxide is separated from the methane increasing the concentration of methane up to pipe-line specifications ($>97\%$) of methane.

Typically 30–60% of the wet biomass input is converted to methane by digestion. The unconverted biomass forms a residue that can be used as fertilizer in agriculture and thus displace energy intensive commercial fertilizers (Lantz et al., 2007). The upgrading process is both energy intensive and expensive but the original feedstock (wet biomass) often comes at a very low cost as there as several benefits and legal requirements for the disposal of wet biomass. Another resource for producing biogas is grasses, maize and sugar beets grown on agricultural lands. Advanced digesters are still in its infancy and further research can increase yields and cut cost substantially the coming years. A future option for utilizing wet biomass can be supercritical gasification that, in theory, can convert all the feedstock to methane as compared to the 30–60% using anaerobic digestion. With supercritical gasification, the wet biomass is gasified at high pressure and high temperature where water is in a supercritical phase ($>373\,^{\circ}$C and >220 bar), i.e. no distinction between gaseous and liquid phase. So far, supercritical gasification exists only in demonstration plants (Mozafarian et al., 2004).

The currently most common production of biologically derived methane is land-fill gas which is a result from the natural process of decomposing organic waste. However, as dumping of organic waste in landfills is being phased out in the EU this resource is set to decrease in the long-term. Furthermore, landfill gas contains nitrogen from the air that is difficult to separate from the methane which makes land-fill gas less favorable to upgrade for vehicle use. Land-fill gas is today typically used for heating purposes and electricity production.

2.2. Gasification of woody biomass

Another possible future route for producing biomethane is to gasify dry woody biomass. Gasification can include a number of different technologies and combinations of technologies with the aim of producing either a clean syngas (hydrogen and carbon monoxide) or a producer gas (mainly hydrogen, carbon monoxide and methane). It is common to distinguish between high temperature (above $1300\,^{\circ}$C) and low-temperature (800–1000 °C) gasification. Low-temperature gasification is the preferred option for biomass gasification due to higher efficiency. For producing biomethane two different low-temperature gasification technologies are currently now under development, indirect gasification and circulating fluidised bed gasification (CFB). Indirect gasification is deemed suitable and economic for small-scale (<100 MW) and CFB is usually the preferred choice for larger scale (>100 MW) gasification plants (Zwart et al., 2006; SGC, 2008).

In indirect gasification part of the incoming biomass is combusted separately in a combustor providing the heat used in the gasifier via a heat exchanger. Indirect gasification is economically attractive in smaller-scales but is difficult to scale up due to the complex heat exchange between gasifier and combustor (Mozafarian et al., 2004).

Circulating fluidized bed gasification is the preferred option for large-scale gasification due to high efficiency. In a fluidized bed the fuel is suspended in a mixture of superheated air and sand, collectively called the "fluid bed". The result is a turbulent mixing of gas and solids. The tumbling action, much like a bubbling fluid, provides more effective chemical reactions and heat transfer. The heat medium (the sand) is separated from the producer gas in a cyclone and recirculated back into the reactor. CFBs can either be air blown or oxygen blown where the preferred choice appears to be the use of pure oxygen in the gasification process. Using oxygen instead of air avoids diluting the producer gas after the gasifier with nitrogen and thereby minimizes the size of down-stream equipment.

Another advantage with low-temperature gasification is that the resulting gas from the gasifier, the producer gas, typically contains up to 40–50% methane on an energy basis, the rest is a mixture of CO, H_2, CO_2 and trace compounds. This methane can be separated directly (called "direct SNG") and the rest of the producer gas can then be cleaned and methanised. The availability to directly separate up to 50% of the energy as direct methane is a possible advantage as the methanisation process usually consumes 20% of the energy content of the producer gas. The relatively low-temperature needed for producing a methane rich gas from dry woody biomass (800–900 °C) enables a high efficiency (60–70%) for converting biomass into methane. The equipment after the gasification step (the methanisation) is relatively low cost and commercially available in smaller-scales

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compared to the competing second generation of liquid and gaseous biofuels (methanol, F–T fuels and hydrogen) that all are based on large-scale economics due to expensive synthesise equipment.

2.3. *Co-producing biomethane*

Biomethane and biogas can be co-produced with ethanol from grains, Second generation liquid fuels such as F–T diesel and methanol and electricity. Co-production increases the overall primary energy efficiency and increases the economic viability and market flexibility.

Biogas can be co-produced with first generation of ethanol production from e.g. wheat. Producing ethanol leaves a by-product (druff) that normally is used as animal fodder. However, the market for animal fodder is limited and with increasing production of ethanol the fodder left over can instead be used for producing biogas. From 1 MWh produced ethanol roughly 0.3 MWh of biogas can be produced if all the druff is used for biogas.

Biomethane and F–T fuels can be co-produced in a gasification process by using a "once through" concept and separating the methane directly from the producer gas. The remaining 45–55% of the producer gas is cleaned and shifted up to syngas and then synthesized to F–T diesel (Zwart and Boerringter, 2005). From any of these concepts, electricity can also be produced in varying degrees depending on the specific settings and economies.

3. Delivering biomethane to the vehicle

Biomethane is a gaseous fuel under normal conditions and this makes distribution, dispensing and storing the fuel in the vehicle more difficult compared to liquid fuels. However, in a major part of Europe, the infrastructure for transmitting, distributing and fuelling methane already exists for compressed natural gas (CNG).

3.1. *Distribution and filling stations*

Biomethane can be distributed via pipe-lines, by truck compressed (CNG) in pressurized bottles or in liquid phase (LNG) in cryonic bottles.

In countries with an existing natural gas grid such as the UK, Italy and Germany, biomethane can be distributed via the existing pipe-line infrastructure together with natural gas, the so called "green gas concept". Furthermore, the transmission lines for natural gas operate at a relatively high pressure (up to 80 bar) whereas local distribution grids operate at a substantially lower pressure (4–30 bar). The pressure drop at connection spots between transmission and distribution lines can be used for producing liquid methane "for free" that could be more easily distributed to vehicles, see concept in SGC (2006). Approximately 25% of the high pressure gas can be converted to liquid methane.

In countries with no natural gas infrastructure such as Sweden, biomethane can be transported either in local pipe-lines or by truck in pressurized bottles (CNG) and dispensed closed to the biogas plant. Another option is to liquefy the methane and to distribute as LNG to increase the energy density for lowering transport costs and if used in the vehicle for increasing the range. LNG has so far been used in heavy duty vehicles for increasing the range. LNG can be distributed to filling station that convert the LNG–CNG for fuelling or to filling station that can supply both CNG and LNG to the vehicles.

Currently an estimated 1500 filling stations exist within the EU (500 of them in northern Italy) for CNG. The most of these were for captive fleets and not public and this should be compared to the approximately 113,000 filling stations for standard fuels in 2004 (Kavalov, 2004). The filling stations for CNG are more expensive compared to standard liquid filling stations (200,000 to 400,000 Euros for a complete station, varying with local circumstances). Filling stations can either receive methane under pressure or as a liquid and can dispense to vehicles either under high pressure (> 250 bar) for fast fill, low pressure over night fill, and as LNG.

3.2. *Vehicles for gaseous fuels*

CNG vehicles are relatively common in several countries. Approximately 8,700,000 CNG vehicles concentrated to Argentine, Pakistan, Brazil, India, Iran and Italy are on the road today. Over 800,000 of these CNG vehicles operate in Europe. The provision of low-cost natural gas and an already built up gas infrastructure for electricity and industrial use has driven the use of CNG vehicles in countries like Italy, Pakistan, Russia, and Argentina. In these countries, the CNG vehicle fleet represent between 10% and 20% of the total fleet (NGVA, 2008).

Biomethane can be stored in vehicles in compressed form as CNG. Here, methane is compressed up to 250 bar for storing in a pressure vessel at 200 bar in the vehicle. The fuelling of a vehicle can be done within a number of minutes but also at lower pressure over night for e.g. fleets that are parked at a central location. A 200 bar vessel gives an acceptable range for passenger cars and buses but is not considered enough for heavy duty trucks. However, even under high pressure the energy density of compressed methane is 1:4 compared to petrol.

For delivery trucks and long haul trucks there is an interest towards using liquefied methane (LNG) due to range limitations. Methane is liquefied by cooling it down to $-162\,^{\circ}\mathrm{C}$ and can be stored in a cryonic double-walled vacuum-insulated vessel. However, the liquefied methane cannot be stored for very long (a couple of days). Even in well insulated vessels the methane will slowly start to evaporate and need thus to be vented. Methane is a very potent greenhouse gas and venting must thus be avoided. An option is a double system with one pressurized tank and one liquid cryonic tank for enabling a good range for the vehicle. Hereby, the venting can push over condensed methane into the pressure tank and thus avoid venting into the air. Double systems using one compression tank and one tank for liquid methane is currently used in some models. LNG has a better energy density compared to CNG but still lower compared to diesel (1.7:1). However, this energy density is still better compared to liquid methanol and similar to ethanol.

A gaseous fuel cannot be mixed with petrol or diesel as compared to low blending of ethanol, F–T diesels or methanol. For methane, bi-fuel vehicle that use double tanks for both petrol/diesel and CNG are used instead. Bi-fuel vehicles offer the flexibility of not being dependent on a readily built infrastructure. In the short-term, this could very well be an effective way of building a reliable market for biomethane. However, the engine in a bi-fuel vehicle cannot be optimized for methane. A dedicated CNG vehicle can be made 10% more fuel efficient due to higher octane rating. Bi-fuel vehicles come at an extra cost, higher weight and less thermal efficiency compared to a dedicated CNG-only vehicle.

Methane can also be used in diesel engine with an igniter. This has been demonstrated in New Delhi, India where all public busses have been retrofitted from diesel to run on methane. Approximately 10% diesel is used as an igniter ("pilot fuel") and the rest of the fuel is methane. There are numerous dedicated built CNG buses around the world today and the local bus fleets

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have been the driving force for using biomethane as a transport fuel.

4. Available resources today and tomorrow

Biogas (not upgraded) has grown substantially the last years within the EU, see Fig. 1, and the production reached close to 0.25 EJ in 2007 which should be compared to 19.7 EJ natural gas consumption within the EU.

The development of biogas has been driven largely by feed-in tariffs (e.g. Germany) and Renewables Obligation Certificates (UK) that both have spawned a market for electricity production from land-fill gas and farm-based methanisation plans. Especially in German has farm production systems based on crops and manure grown substantially the last years and now accounts for up to 70% of the biogas production in Germany (Biogas barometer, 2005-2008). As a whole however, the biogas production from land-fill gas and sewage sludge still dominates within the EU.

The potential supply from wet manure, sewage sludge and food processing residues is estimated to 0.8 EJ up to 2030 (EEA, 2006) as compared to the current production of 0.25 EJ (see Fig. 1). This estimate also includes a general decrease of waste streams in accordance with other environmental ambitions such as increasing overall resource efficiency (ibid).

The environmentally compatible biogas potential from dedicated grass grown on agricultural lands within the EU up to 2030 is 2.15 EJ (EEA, 2006). The potential from agricultural lands denotes cereals, oil crops, grass (cuttings), maize double cropping systems and perennial grasses especially suited for fermentation to biogas. Growing crops for biogas on agricultural lands is expected to increase after 2015 due to double cropping systems. The expansion of double cropping systems will not compete with food production nor the production of woody biomass from e.g. short rotating forest.

The potential for woody biomass is larger. The total environmentally compatible potential up to 2030 is estimated to 12.3 EJ whereof 4 EJ from waste streams, 2.3 EJ from forestry and the rest from agricultural lands (EEA, 2006). The potential for woody biomass is however disputed and Ericsson and Nilsson (2006) give a technical potential of up to 17 EJ for EU-27

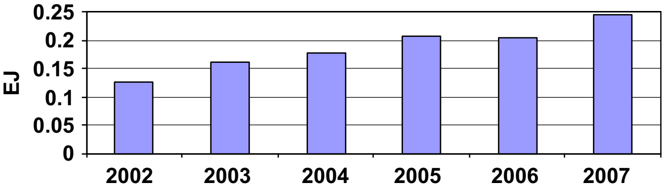

Fig. 1. Biogas production development between 2003 and 2007. *Source*: Biogas barometer, (2005–2008).

4.1. Matching demand and supply

The potential supply can be compared to the current energy use in the EU transport sector of approximately 12 EJ (whereof 5 EJ to freight) that is projected to grow in a business as usual scenario up to 15 EJ (8 EJ freight) by 2030 (EU-Trends, 2003). This scenario assumes a forced efficiency of passenger cars in the EU down to 120 gCO_2/km and a normal efficiency development of freight transport. As an example of higher efficiency, Åhman and Nilsson (2008) have shown in a "rapid energy efficiency scenario" that the EU-Trends scenario can theoretically be lowered down to 9.6 EJ (whereof 6 EJ is freight) if high energy efficiency is highly prioritized. This technical potential for energy efficiency might never be realized but since the publication of the EU-Trends scenario in 2003 the EU-commission have indicated a long-term goal of 95 gCO_2/km by 2020 for new passenger cars and that light busses and light truck also will face tougher efficiency regulations.

Of the current 12 EJ of transport fuels, only 0.02 EJ is natural gas and 0.15 EJ is light petroleum gases (LPG) used mostly in heavy traffic. About 0.3 EJ of the total transport fuel demand is used for "public road transport" (mainly local busses) according to EU-Trends (2003).

In Fig. 2, the potential biomethane supply in the EU-25 in 2030 is given. The general assumption in Fig. 2 is that all suitable biomass resources are assumed to be used for biomethane. However, all biomass will not be available for the transport sector as other sectors also need to phase out fossil fuels and will thus be competing for the limited biomass resources.

The *technical* potential for biomethane is thus large and as an example, a 20% share of biomethane in the EU-25 transport sector in 2030 would need to use 40% of the potential wet biomass supply and 33% of the potential woody biomass supply within the EU. Furthermore, with increased energy efficiency (see RAFF scenario) in the transport sector these numbers could be lowered to 30% of the wet biomass and 20% of the woody biomass.

5. Economics of biofuels

5.1. Production, distribution and dispensing costs

The current and potential costs for all fuels discussed here are compared in Fig. 3. The costs shown are estimated production costs including distribution and dispensing. Taxes are excluded

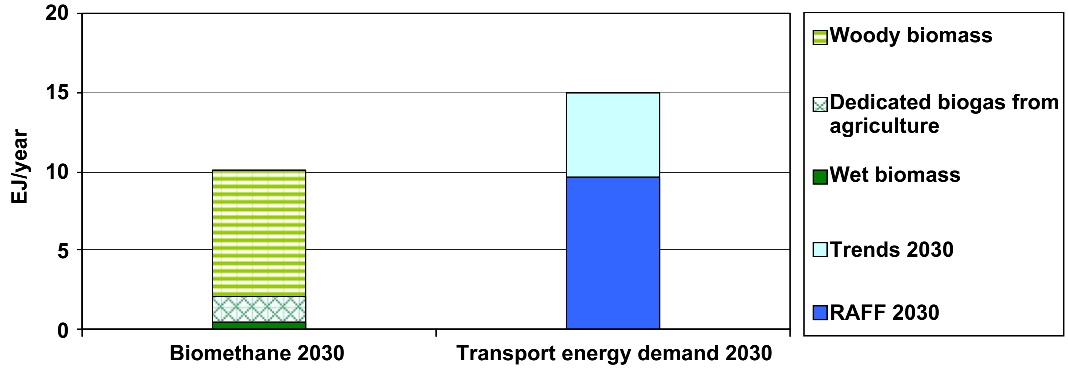

Fig. 2. Potential biomethane production and future transport energy demand 2030 for EU-25. *Notes*: RAFF denotes RApid eFFiciency scenario and illustrates the technical efficiency potential up to 2030 and is further explained in Åhman and Nilsson (2008). *Sources*: Åhman and Nilsson (2008), EU-Trends (2003), EEA (2006, 2007).

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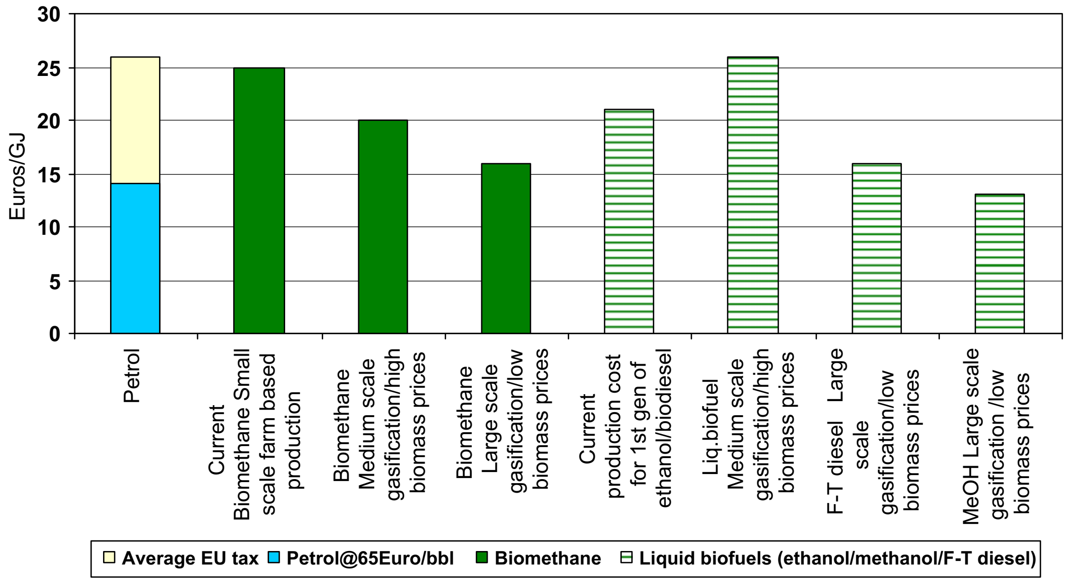

Fig. 3. Current and potential production, distribution and dispensing costs for biofuels and petrol. *Notes*: near term costs are based on Concawe et al. (2007) with an oil price of 65 Euros/BBL. Farm-based biogas production assumes centralized upgrading. Medium and large-scale production costs for biofuels are based on Hamelinck and Faaij (2006), Mozafarian et al. (2004), Zwart (2007) and adapted with authors own calculation reflecting the higher biomass price (high biomass). Distribution and dispensing costs are based on Ecotraffic (2002), Concawe et al. (2007), IEA (1999), distribution costs for biomethane was based on SGC (2008) and refers to a mixture of gas transported in pipe-lines and in cryonic bottles as LNG.

except for petrol where the average tax-level within the EU is indicated. The medium (100 MW) and large (> 400 MW) scale costs denotes the potential costs assuming technical development for some crucial components and learning effects. The future input price of woody biomass is either assumed to be 2.3 Euros/GJ (low biomass) or 4.5 Euros/GJ (high biomass). The current costs for woody biomass ranges between 2.9 for waste wood up to 4.9 Euros/GJ for dedicated plantations (Concawe et al., 2007). Supplying biomass at a cost around 2.3 Euros/GJ requires substantial market development to ensure competition, the utilization of the relatively large amounts of low-cost waste streams and development of dedicated bioenergy on abandoned crop lands. Another necessary requirement is that the currently growing global trade of biomass is further expanded to include regions with high potential for low-cost production of woody biomass (e.g. Sub Saharan Africa, South and Latin America). In a high growth global economy where the demand for biomass could increase rapidly the availability of biomass will become restricted and the prices will become demand driven and thus substantially higher.

As can be seen from Fig. 3, the potential large-scale production costs for second generation of fuels, including methane, need not be substantially more costly compared to current petrol prices excluding taxes. As can also be noted, all the cost projections are very dependent on the emergence of an efficient market for low-cost woody biomass. The cost of woody biomass constitute more than a third of the potential costs of biofuels.

The short- and medium-term costs for biofuels are substantially higher compared to petrol. As an example, current farm-based production of biomethane (biogas+upgrading facilities) is estimated to between 20 and 28 Euros/GJ depending on the size of the digester (Concawe et al., 2007; SGC, 2008). This is close to twice the cost of petrol today. Current production of ethanol (from wheat) and biodiesel is estimated to cost around 21 Euros/GJ in the EU.

Comparing the potential cost and the assumptions for the different biofuels alternatives reveals some interesting points. Biomethane from gasification has an advantage compared to methanol and F–T diesel of less dependent on technical development and learning by doing, two substantial components for attaining the low cost for liquid second generation of biofuels given in Fig. 3. Methanol and Fischer–Tropsh diesel both require a more advanced and scale dependent synthesis step compared to methanisation. Another advantage for biomethane that could reduce the cost is the potential use of methane directly from the producer gas (“direct SNG”). This can make biomethane less costly in a medium scale compared to producing liquid syngas derived fuels in the same scale.

The average taxation including both energy taxes, CO_2 taxes and VAT on petrol and diesel in the EU ranges from 50% to 75% of the total cost and is indicated in Fig. 3. In the short- and medium-term, the high taxation leaves the EU countries a room for manouver to introduce alternative fuels by allowing tax reductions.[2] This is what currently is happening in some EU countries for introducing first generation of biofuels.

Not included in the cost comparison in Fig. 3 above is the fact that gaseous fuel vehicles such as methane and hydrogen vehicles is inherently more expensive compared to ethanol, methanol and F–T fuels vehicles due to the need for installing a pressurized tank. A dedicated CNG vehicle is estimated to cost 1953 Euros more in the short-term compared to a conventional vehicle according to Concawe et al. (2007) and a bi-fuel vehicle 2538 Euros more (ibid). With development and market experience this incremental cost can decrease but for private users the extra up-front cost and the lack of refuelling stations has so far proven to be a major obstacle for wider private use even in countries with CNG prices substantially lower compared to petrol.

A large part of the higher alternative fuel cost can be compensated by the user by driving a more energy efficient vehicle. However, increasing energy efficiency by introducing advanced technologies such as hybrids electric vehicles will increase the vehicle cost compared to conventional vehicles. As an example, HEVs reducing fuel consumption with approximately 25–50% are assumed to cost 3000–6000 Euros more to produce

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[2] The taxation can be suspended for a while when introducing alternative fuels but the loss of tax revenue needs to be compensated sooner or later.

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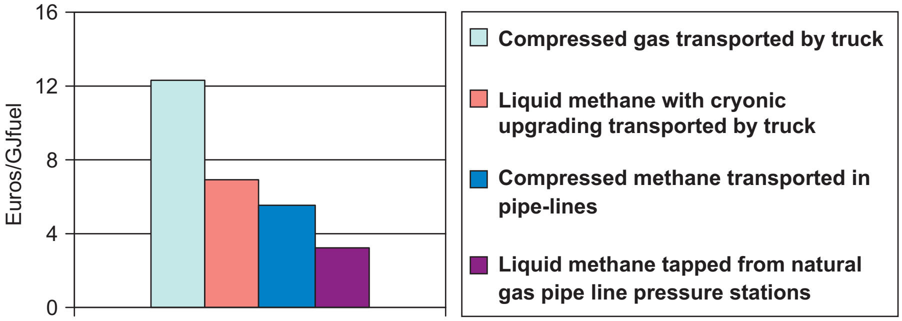

Fig. 4. Cost for distribution and dispensing of biomethane at medium scale. *Source*: SGC (2006), Zwart (2007).

compared to a conventional vehicle,[3] see Concawe et al. (2007); Lipman and Delucchi (2003).

5.2. *Distribution and dispensing—a detailed look*

The cost of distributing methane is substantially higher compared to liquid fuels, from 2 to 3 Euros/GJ for liquid fuels to 5–12 Euros/GJ for methane. In Fig. 4 above the distribution cost is assumed to be a mixture of pipe-line distribution and distribution by truck in cryonic bottles at an average cost at 6 Euros/GJ. This is the most likely system in the medium to long-term. In Fig. 4 below, the estimated costs for different distribution and dispensing alternatives that are given.

Today, most biomethane is distributed locally and dispensed close to the point of manufacturing. The high cost for distributing biomethane by truck in pressurized vessel may seem prohibitively expensive but is still used today for back up and for distant fuelling station. Distributing and dispensing liquified biomethane has not developed to a greater extent yet.

The long-term solution for gaseous fuels like methane and hydrogen usually relies on pipe-lines but these require up-front capital investments and a secure market. Note the low price for liquid methane from tapping off the pressure reducing stations along the natural gas transmission lines. However, this “resource” is limited it can act as a sensible low-cost introduction to liquid methane.

6. Efficient use of biomass

6.1. *In which sectors should biomass be used?*

Biogas is a high quality energy carrier that can be used in a number of applications with high efficiency. The market for biogas (both supply and demand) has so far been policy driven. The *production* of biogas relates to several policy objectives such as environmentally friendly waste management, rural development, security of supply and mitigating climate change. However, where to *use* the biogas is predominately motivated by the ability to replace fossil fuels and thus mitigating climate change.

Biomass has the potential to partially replace fossil energy in both the transport, the heating and in the electricity sectors. It is generally considered that the most cost and energy efficient way of using biomass in the short-term is to replace coal in heating system. Thereafter for replacing coal for electricity generation and lastly for replacing crude oil derived petrol and diesel (Gustavsson et al., 1995). This is also confirmed by the actual development in countries with a strong biomass development such as Sweden where only 3–4% of the supplied bioenergy is used in the transport sector and around 80% is used in the heating sector (STEM, 2008).

However, in the longer term the cost efficient allocation of biomass resources remains inconclusive and strongly dependent on the development of alternative non-bioenergy sources within the heating and electricity sector. If cost efficient non-bioenergy alternatives such as solar cells, off shore wind power, solar heating, will successfully develop for heating and power production then biomass derived fuels may be the only CO_2 neutral option for the transport sector (at least for air craft and long distance road transport). As an example, Gielen et al. (2002) and Azar et al. (2003) come to opposite conclusions regarding the long-term cost efficient allocation of biomass resources. In the scenario developed by Gielen et al. (2002) all biomass is allocated to the transport sector in the long-term whereas Azar et al. (2003) allocates all biomass to the heating and electricity sector and none to the transport sector where they assume that solar derived hydrogen in combination with fuel cells vehicles will be the main renewable option in the year 2050 and beyond. The main differences between these two studies are their differing assumptions on whether solar hydrogen and fuel-cell development will ever be competitive.

Add to this, that the above cost efficient allocations cited above are all based on pure conversion routes, e.g. that you either produce heat, electricity or transport fuels. Most current development of biofuel conversion technologies are based on polygeneration concepts, i.e. producing both fluid fuels, heat and electricity. This will make a separate and rational allocation to any of the three different sectors more difficult. However the unprocessed route of burning woody biomass directly producing low quality heat will continue to be the most simple and low-cost route of producing any form of energy from biomass. Biogas is different from woody biomass with a higher end use quality from the start which makes the option of replacing fossil fuels in more difficult sectors such as the electricity and transport sectors, more attractive compared to the heating sector.

The development of the user market for biogas and biomethane will be driven by differing policy objectives that will have to deal with the inherent uncertainty regarding both long-term fossil energy use reduction ambitions and long-term technical development of other renewable technologies in all sectors. This market development will also have a memory, meaning that the development will follow certain paths and that is thus highly unlikely that we will see a “perfect foresight” development as suggested in the energy-economic models cited above. In conclusion, biomass resources, both woody biomass and biogas from wet biomass, will be used for a variety of purposes, e.g. heating, electricity, transport. There are sufficient strategic reasons for continuing to develop the market for bioenergy in the transport sector.

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[3] This is not necessarily reflected in the price.

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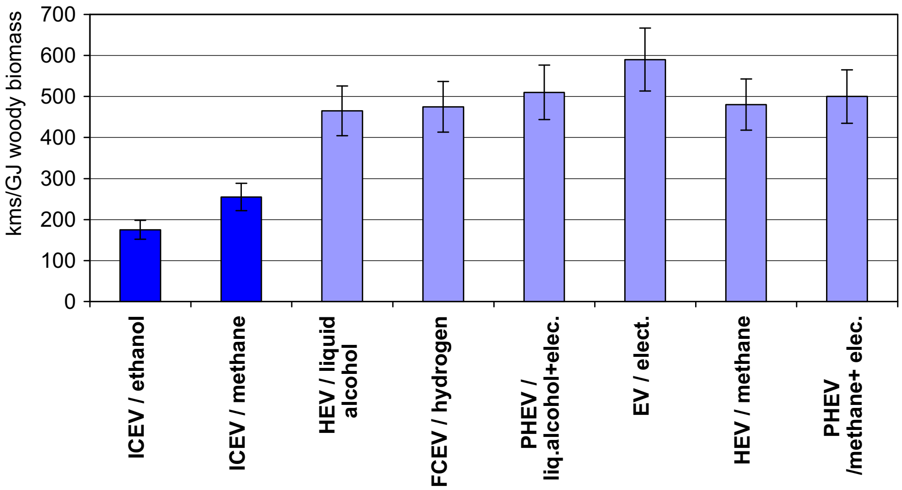

Fig. 5. The driving range from using 1 GJ of woody biomass for vehicle and fuels technologies. *Notes*: calculation based on: for vehicles updated Åhman (2001) and Weiss et al. (2000); for biofuels derived from woody biomass; Faaij (2006) and Zwart (2007). Calculation taken into consideration the weight penalty induced by batteries in EVs (300 kg), HEVs (100 kg), and PHEVs (150 kg) and the weight penalty from gaseous storage tank for methane vehicles (50 kg). All numbers refers to a theoretical standard four door sedan mid-size passenger car and normal driving patterns (see Åhman (2001) for more details) and includes all up stream losses from e.g. gasification, compression, etc. For PHEV and EVs; electricity assumed to come from biomass generated electricity with 45% efficiency.

6.2. *Comparing the efficient use of woody biomass for transport*

From woody biomass it is possible to produce a number of different biofuels and electricity. In Fig. 5 below the distance you can drive per GJ of woody biomass is given for biofuel candidates including biomethane and for biomass derived electricity.

The calculations are based on the primary energy efficiency starting from the woody biomass and including losses in the fuel distribution and losses within the vehicle (from well to wheel). In Fig. 5, the primary energy efficiency for both current as well as potential vehicle and fuel technologies are given. The potential efficiencies are however uncertain and reflect what can be potentially achieved if energy efficiency is prioritized.

Producing biomethane has an overall higher efficiency compared to DME, F–T fuels or hydrogen which of also improves the economy. The energy efficiency of producing biomethane is potentially around 60–70% (Mozafarian et al., 2004). This can be compared producing methanol with 55–60%, F–T fuels with 45–50% and hydrogen with 60–65% potential efficiencies in large-scale developed gasification facilities (Faaij, 2006).

New alternatives, such as plug-in hybrids and electric vehicles (EVs) that uses electricity requires new advanced batteries as well as further development of the electric drivetrain. Thus, in order to compare the primary energy efficiency of using electricity to using biofuels in a fair manner, the technology level regarding the electric drivetrain and batteries are assumed the same for HEVs, PHEVs and EVs. This means that the assumed efficiencies for HEVs are higher compared to today due to assumed technical development. The assumed efficiencies for fuel production are based on estimates of future efficiencies from thermal gasification (Faaij, 2006) apart from current ethanol production from woody biomass via enzymatic hydrolysis. Ethanol from woody biomass has however a potential to attain similar efficiencies as methanol from gasification (Hahn-Hägerdal et al., 2006).

As can be seen from Fig. 5, there is a substantial potential for improvement for all fuels and vehicles considered. In order for the limited biomass resources to have a global impact and to become economically reasonable it is imperative that energy efficiency is a crucial part in development. Another interesting point is that from a well to wheel perspective and with the large uncertainties involved there is no clear outright winner, all can potentially travel around 500 km on one GJ of wood given the uncertainties. A pure battery electric vehicle has some advantage over a HEV but the difference is relatively small. Furthermore, it is far from clear today if pure electric vehicles will ever become a commercial alternative.

7. The role of natural gas and the existing grid

7.1. *Natural gas in the EU*

Natural gas supplied 19.7 EJ of energy in the EU in 2007 which corresponds to over 20% of the total primary energy supply. About 7.7 EJ of this natural gas energy was produced within the union and the rest imported. The European gas resources are mainly located to the UK and the Netherlands. However, these reserves are decreasing and compensated by increasing imports from Norway, Russia and the Middle-east (Kjärstad and Johnson, 2007).

'An increased use of natural gas was endorsed by the European commission in the early 2000s. The main reason for this support was security of supply concerns by means of diversifying the energy supply away from middle-east oil imports. A second reason is environmental as modern natural gas power plants can replace conventional coal power plants resulting in up to 50% decrease in CO_2 emission per MWh electricity (Concawe et al., 2007). In the transport sector, natural gas used in CNG vehicles was also endorsed and included in the EU-commissions plans to replace 10% of petrol and diesel with "alternative fuels" (EU contacts group, 2003). Natural gas driven vehicles generally emit 25% less CO_2 per energy unit compared to petrol or diesel vehicles (IEA, 1999; Concawe et al., 2007).[4] However, the increasing debate on climate change has led the commission and its member states to focus on renewable transport fuels instead of "alternative" thus excluding CNG. Add to this the developments in Russia that has put the arguments of security of supply in serious doubt (Larsson, 2007). Currently, natural gas is viewed more cautiously within

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[4] Today, Italy is the major user of natural gas for vehicles in the EU. Small fleets also exist in France, Germany, Sweden and Ireland. Globally, several countries with ample gas supplies have been using natural gas for long such as Russia, Argentina and Pakistan.

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the EU. However, the expansion plans for natural gas fired heating and electricity plants are still ambitious and new transmission lines from Russia to middle-east are prospected and built and natural gas is increasing rapidly with 1.9% every year (Euro Gas, 2008).

7.2. Dual-use of gas grid

The transmission lines, the underground storage, and the distribution network for natural gas can be used for supplying biomethane as well. There are obvious economic and technical advantages to use the already existing large-scale transmission and distribution system. The existence of a mature market for supply and demand for "gas grid quality" methane helps to create stability in an emerging market for both prospective users and suppliers of biomethane.

An example of the strong links between the interest in developing large-scale biomethane production and the existence of a transmission system for natural gas can be found in the Netherlands where natural gas supplies around 50% of the primary energy. Here, biomethane has been identified as a strategic interest and the Dutch government has developed a vision to replace 20% of the natural gas in the transmission system with biomethane from gasification of imported woody biomass (Boerrigter, 2006). The possibility of the gas transmission and distribution system to become an equally flexible and complementary energy carrier as the electricity system supplying energy to industry, electricity and the transport sector is a tempting vision. However, in order to include the transport sector, the existing distribution system needs to be complemented with more filling stations for vehicles.[5]

As mentioned earlier, a "green gas concept" similar to the existing "green electricity concept" has been proposed in order to account for the green gas in the distribution system shared with gas from fossil origin (SGC, 2008; Boerrigter, 2006). This is a technical accounting system that could easily be introduced when there is a need for legal, economic or other reasons to separate the use of methane from fossil or biological origin. Another reason for developing a green gas concept is to create legitimacy and public acceptance among biomethane interest groups for using the natural gas grid.

7.3. Biomethane or natural gas in the grid?

When sharing infrastructure with natural gas, biomethane needs not only to be competitive compared to petrol and diesel but also needs some sort of policy created advantage (e.g. mandate or a CO_2 tax) to make it competitive with natural gas in the distribution system. This can be done by legislation e.g. a "green gas" quota or something similar or with an economic incentive, e.g. a CO_2 tax.

Used in a vehicle, compressed natural gas (CNG) emits 64.6 kgCO_2 ekv/GJ fuel compared to compressed biomethane from wood that emits only 6.4 kgCO_2 ekv/GJ fuel (Concawe et al., 2007). This would mean that a CO_2 tax of 50 Euros/ton CO_2 would give an extra cost of natural gas compared to biomethane of 2.9 Euros/GJ.

The price of natural gas has traditionally followed crude oil and has been set to 80% of the crude oil price on an energy basis. A crude oil price of 65 Euros/barrel[6] translates thus to a natural gas price of 8.6 Euros/GJ. Adding cost for pump stations and handling this would mean a CNG price of 10–11 Euros/GJ at a pump station located along the natural gas grid and 14–15 Euros/GJ if new distribution systems are needed. This is far below current farm-based biomethane prices 25 Euros/GJ shown in Fig. 3 and would require a CO_2 price of >150 Euros/GJ. However, in Fig. 3 the potential cost reduction including large-scale production, technical development and low-cost supply of biomass shows a possible cost of biomethane from gasification of woody biomass at ~ 16 Euros/GJ supplied to the vehicle. This is within range of the natural gas option.

The long-term low cost of producing biomethane from woody biomass illustrated in Fig. 3 is partly due to assumptions on an abundant supply of low-cost woody biomass from imports or waste streams at an estimated cost of 2–3 Euros/GJ. However, as demand for biomass increases with more ambitious mitigation efforts the price of biomass could increase. The current cost of producing woody biomass from dedicated plantations is estimated in the EU to 4.5 Euros/GJ (Concawe et al., 2007) which would result in a biomethane cost of 20 Euros/GJ (see Fig. 3). Another long-term issue is what will happen to the oil and gas price in a world with strict climate policies. Several outcomes are possible for natural gas as crude oil prices most likely will decrease due to decreasing demand but at the same time a possible increase in the demand for natural gas as a low carbon intermediate replacement of crude oil and coal.

8. Development needs and barriers for biomethane and liquid biofuels

Strong technical and market development are needed for mitigating a major share of the growing dependence of crude oil derived fuels in the transport sector. The focus for long-term development have the last 20 years centered around second generation of liquid biofuels such as ethanol, methanol and Fischer–Tropsh diesel from gasification and enzymatic ethanol. This paper argues that these efforts should be complemented with a concerted effort to develop biomethane as well building on the integration with the existing energy, fuel and vehicle infrastructures that already exist.

The obvious disadvantage of biomethane compared to second generation of liquid biofuels is that it in gaseous form at normal temperature and pressure and thus require a new infrastructure and adopted vehicle technologies, especially a more costly fuel tank. The problems with more complicated vehicle technologies are not insurmountable with 8.7 millions of CNG vehicles globally already in place and the possibility to take advantage of the already existing distribution systems for natural gas. However, policy incentives will be needed for the private car market to overcome up-front costs and low availability of fuelling stations in the short- and medium-term.

The advantages of biomethane compared to second generation ethanol, methanol and synthetic diesel are several:

(i) Biomethane from wet biomass are available today and the technical and economic barriers for producing biomethane from woody dry biomass by gasification are small. In the concept that requires least technical development you just separate the "direct SNG" from the producer gas and use the rest of the producer gas for heating in a district heating

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[5] Note that the dual-use argument that natural gas transmission lines can support the development of biomethane applies poorly for building new transmission lines due to the likelihood of crowding out local bioenergy demand (Neij et al., 2007).

[6] Long-term (to 2030) projections of crude oil prices by IEA (2007) and OPEC (2008) suggest a crude oil price of 60–70 USD/barrel.

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system. Enzymatic hydrolysis of woody biomass to produce ethanol is still on a basic research level in development. To synthesise methanol or Fisher–Tropsch diesel a very clean syngas is needed. In order to produce this commercially a low-temperature gasification process is needed for attaining high efficiency but low-temperature gasification produces tars and requires the development of hot gas cleaning that is not yet developed at a commercial scale.

(ii) Biomethane can be produced cost efficiently at low–medium scales today (20–100 MW) whereas liquid second generation alternatives (ethanol and methanol and F–T diesel) all require large-scale production due to the synthesis step in order to meet cost criteria.

(iii) Biomethane can also be derived from woody biomass via gasification but have as well the feedstock flexibility to use wet biomass streams compared to ethanol, methanol and Fischer–Tropsch diesel.

(iv) Biomethane distribution can be integrated into the existing natural gas distribution network.

In conclusions, biomethane is comparatively less dependent on specific technical developments, less dependent on scale of production, have somewhat greater feedstock potential, and can be integrated into the existing EU-wide natural gas grid as well. Biomethane exhibits a clear development path from production and use of biogas from wet biomass at a local scale towards a medium and regional scale where gasification of woody biomass can be applied. Benefiting from the possibility of dual-use with natural gas paves the way for further expansion up to a national large-scale. In the long-term, a larger scale production of biomethane from gasification with an infrastructure dedicated to biomethane based on pipe-lines could be an option.

9. Conclusions

Biomethane is already gaining ground as a local fuel for both transport, heat and electricity. This development is largely driven by local initiatives and predominately by concerns for local air pollution and waste management. However, the last five years, biomethane has also been identified as an excellent fuel from a climate change mitigation perspective. Biomethane and all other non-fossil alternatives will have difficulties to compete economically with fossil derived fuels in the short- and medium-term. However, in a climate restricted world where close to all energy will have to become carbon neutral in the coming 50 years renewable fuels will be compared to each other and to fossil derived fuels.

This assessment concludes that biomethane should not only be considered as a local and small-scale option but also a large-scale future contender with reasonable economics. The use of scarce biomass resources as biomethane is comparable to the alternative uses in the transport sector such as methanol ethanol from an efficiency point of view. The development of biomethane will have strong links to the already existing natural gas distribution network across Europe. This link will not act as a barrier or carbon-lock in but can be used efficiently to help the development of large-scale biomethane if the right policies are adopted such as green gas quotas. Biomethane also exhibits a clear development path with relatively low financial and technical risks starting with local solutions at small scales utilizing wet biomass resources towards medium scale gasification of woody biomass. The large-scale production of biomethane has comparable economics to the liquid second generation biofuels such as ethanol, methanol and Fischer–Tropsh diesel.

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