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# Biogas as a resource-efficient vehicle fuel

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**There are currently strong incentives for increased use of renewable fuels in the transport sector worldwide. However, some bioethanol and biodiesel production routes have limitations with regard to resource efficiency and reduction of greenhouse gases. More efficient biofuel systems are those based on lignocelluloses and novel conversion technologies. A complementary strategy to these is to increase the production of biogas from the digestion of organic residues and energy crops, or from byproducts of ethanol and biodiesel production. Compared with other biomass-based vehicle fuels available so far, biogas often has several advantages from an environmental and resource-efficiency perspective. This provides the motivation for further technological development aiming to reduce costs and thereby increased economic competitiveness of biogas as a vehicle fuel.**

## Introduction

Today, ethanol from cereals and biodiesel from rape seed are the two major biofuels obtained from agriculture in Europe, and the production of both fuels is increasing rapidly [1]. Internationally, the trends are comparable, but the crops used vary from country to country. In the USA and Brazil, bioethanol is the most important liquid biofuel and is produced from corn and sugar cane, respectively. The USA and Brazil contribute >70% to world production of bioethanol, whereas Europe contributes ~6% [2]. In Germany production of biodiesel from rape seed is the most exploited liquid biofuel process, whereas in South East Asia oil palms are cultivated on a large scale for biodiesel. The current increased interest in biofuels is due to several factors, including: (i) high profitability for farmers cultivating these crops for energy purposes, driven by various incentives, as compared with production of these crops for food or feed; (ii) the existence of commercial technologies for fermentation of cereals and for oil extraction from oil crops; (iii) an existing infrastructure that can be used for the distribution of the biofuels (e.g. ethanol can be blended with petrol and biodiesel into diesel); and (iv) the suitability of biofuels for use in existing cars – bioethanol is used in ordinary petrol-fuelled cars and biodiesel in diesel-fuelled cars.

Moreover, various incentives within energy, climate and agricultural policies exist in several countries to promote progress in this direction. For example, in January 2007 the European Commission adopted new guidelines for an ambitious energy policy for Europe with a binding target of increasing the level of renewable energy in the EU from the current level of <7% to 20% by 2020. Within the strategy is a binding minimum target for 10% renewable transportation fuels by 2020. Energy crops are considered important means for reaching these targets [3]. Incentives also exist within the Common Agricultural Policy (CAP) in the EU to encourage farmers to cultivate energy crops. Thus, there are several strong incentives stimulating the production of biofuels from agriculture, both within and outside the EU [4].

Based on the factors listed above, the so-called 'first generation' of biofuels is expected to dominate renewable transportation fuels for the next ten years. However, when considering a long-term perspective, new biofuel production systems need to be developed because several of the 'first generation' biofuels, such as ethanol from wheat and corn and biodiesel from rape seed, have limitations regarding their resource efficiency. This is particularly relevant if byproducts from production processes are not used efficiently [5,6]. Examples of the emerging 'second generation' of biofuels are vehicle fuels based on lignocellulose and fuels produced by thermal gasification, including methanol, dimethylether (DME), Fischer-Tropsch (FT) diesel and methane, as well as bioethanol produced by hydrolysis and fermentation. However, these novel conversion technologies are not yet commercially available.

Another alternative and complementary option is the production of biogas by anaerobic digestion of energy crops. Biogas can also be produced from organic residues from agriculture (e.g. manure and crop residues), from byproducts from the production of ethanol from cereals (distiller's waste) and from by-products from biodiesel production from rape seed (rape meal and glycerol). Current biogas production is mainly based on sewage sludge in municipal waste-water treatment plants. The production and use of biogas as a vehicle fuel is increasing in Sweden and now exceeds the use of natural gas as vehicle fuel [1]. Sweden has taken the lead in this development but biogas as vehicle fuel is also used in Switzerland, and there is emerging interest and continuing development in the area in other countries, including Germany, Austria, France,

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Spain, India, China and the USA [7,8]. To date, almost all of the biogas produced worldwide is used for heat and electricity production. The development of biogas production for use as vehicle fuel is hampered by several factors: (i) the poorly developed commercial market in biogas technology and the need to improve the quality of the resulting biogas for vehicle fuel use; (ii) the limited distribution systems and number of biogas filling stations; and (iii) the higher costs of dual-fuel vehicles compared with vehicles using either ethanol or biodiesel [9].

In summary, although the exact circumstances might differ from country to country with regard to which biofuel is preferred, the trends towards an anticipated rapid increase in consumption are comparable. The increased demand for vehicle biofuels will stimulate the development of both the product and the production process. The anticipated increase in consumption also means that it is becoming increasingly important to evaluate factors such as area efficiency, which is the distance a car can run using a biofuel from crops harvested from a certain area.

In this paper, the potential benefits of increased use of biogas as a vehicle fuel are discussed by comparing biogas with other biomass-based vehicle fuels from the points of view of energy efficiency and environmental aspects. The overall conclusion is that biogas has several advantages over the two liquid biofuels (biodiesel and bioethanol) that are the current focus of vehicle biofuels. This provides incentives for further technological developments in biogas production systems with regard to cost reductions, which could increase its competitiveness as a vehicle fuel.

**Table 1. Energy content of various fuels**[a]

| Fuel | Energy content (MJ per $dm^3$) |
|---|---|
| Petrol | 31.3 |
| Diesel | 35.6 |
| Ethanol | 21.2 |
| Biodiesel (RME)[b] | 33.1 |
| Methane (per $m^3$)[c] | 35.3 |

[a] From Ref. [11].

[b] Rape methyl ester.

[c] Methane is compressed to 200 bar when used as a vehicle fuel.

## Resource efficiency in biofuel systems

From the perspective of resource efficiency, biogas production from energy crops, such as ley crops, maize and sugar beet, is attractive due to the high energy yield per hectare of arable land (Figure 1, Table 1) [10]. For example, the gross energy output of upgraded gaseous vehicle fuel is higher than for ethanol produced from the same crops or biodiesel produced from rape seed grown on the same amount of arable land. The energy input in biogas production is also calculated to be lower than in current ethanol production and this leads to a higher energy output-to-input ratio for biogas systems. Biofuel based on woody energy crops such as willow (short-rotation energy forest), and biofuel produced by thermal gasification have the highest energy output-to-input ratios.

However, the energy input in biofuel production systems can be calculated in different ways depending on whether potential byproducts are taken into account. In this paper, the allocation of the energy input between the biofuel and a potential byproduct is based on the amount of energy in the biomass feedstock that ends up in the biofuel and in the byproduct, respectively. For example, in current ethanol production from wheat ~65% of the energy in the biomass feedstock will end up in ethanol and ~35% in the distiller's waste [10]. The energy in the byproduct is then compared with the energy in the initial feedstock crop, and the energy input of the feedstock crop is then reduced appropriately. However, currently several different allocation methods exist, which might be relevant under different circumstances. Extended analyses of how the energy balance of biofuel production systems varies depending on the allocation method used have been published elsewhere [5,6,11,12]. Other important parameters that influence the energy balance are local production

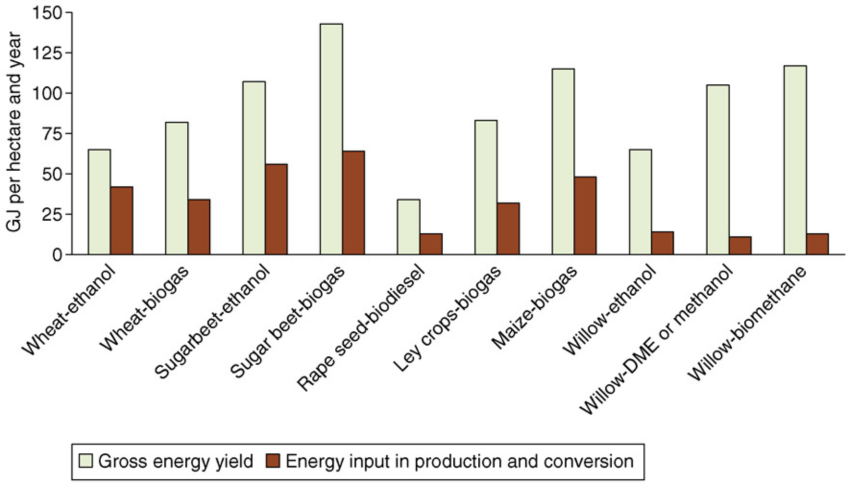

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**Figure 1**. Resource and energy efficiency for production of biofuels from selected energy crops. These crops were cultivated in southern Sweden on average agricultural land. Green bars show gross energy output per hectare and year in the form of refined liquid or gaseous vehicle fuels. The energy input in cultivation and biofuel conversion is shown in brown. Allocation of by-products is based on their energy content and the resulting reduction of the energy input in cultivation (see text for more details about the calculations). By-products in cultivation (i.e. straw in wheat and rape seed production and tops and leaves in sugar beet production) are not included. 1 $m^3$ oil = 35 GJ. Data are taken from Ref. [2].

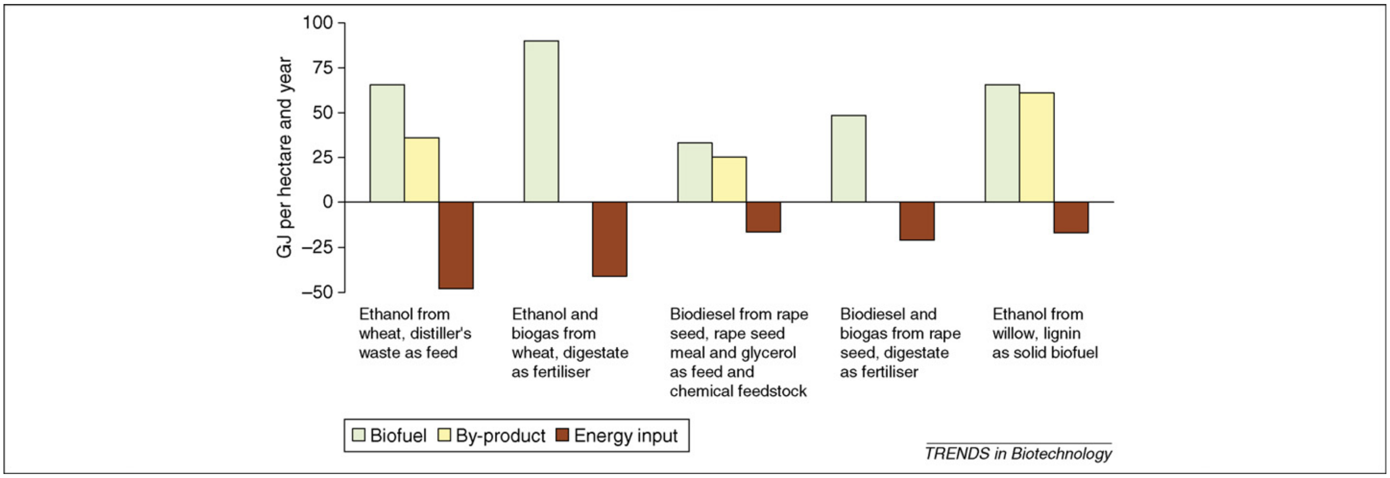

**Figure 2**. Production of biofuels (green columns) and byproducts (yellow columns) from wheat, rape seed and willow (short-rotation energy forest), expressed as GJ per hectare and year. Crops were cultivated in southern Sweden on average agricultural land. The energy inputs required for the respective production chains are shown in brown columns. By-products in cultivation (i.e. straw in wheat and rape seed production and tops and leaves in sugar beet production) are not included. Data are taken from Refs [5,6,10].

conditions, crop yield, cultivation methods, process technologies and systems boundaries [12–14][*].

Biogas from energy crops is preferably produced by co-digestion with manure and other organic waste products, which leads to synergistic effects with regard to energy efficiency and increased biogas yields. Organic waste products, such as manure, are free of charge for biogas production and are not used in other ways (e.g. combustion) for generating energy. Digestion of manure also improves its properties as a fertilizer [15]. In addition, digestion of byproducts from existing cereal bioethanol production systems and from rape seed biodiesel production will improve the energy efficiency of these biofuels (Figure 2). The concept of ‘bio-refinery’ is particularly relevant if there is a limited market for these byproducts. One potential use is to add byproducts rich in protein to feed for farmed animals. Currently, distiller's waste from wheat-based ethanol production and rape seed meal from biodiesel production are used as protein feed mainly for milk production in Sweden and in other European countries [10,11]. If these byproducts replaced imported soy protein, and the resulting reduced transport is included in the energy analysis, then the energy-efficiency of ethanol and biodiesel production systems could be increased [4,5,11]. However, further expansion of the production of ethanol and biodiesel will eventually lead to a surplus of byproducts used in animal feed and after subsequent market saturation, new and efficient uses for these byproducts will be required. For example, glycerol generated in biodiesel production is mainly used as feedstock in the chemical industry and this could also be a viable option for the other byproducts. As a comparative example, the generation of lignin as a byproduct in ethanol production from short-rotation energy forest (willow) is shown in Figure 2. The lignin can be used, for example, for large-scale combined heat and power production or as feedstock for production of wood pellets used in small-scale boilers. This would also be a potential alternative use for rape seed meal and distiller's waste after drying. In future bio-refinery concepts, by-products from cultivation of energy crops (e.g. straw from cereal and oil seed production) could also be utilized, for example, as fuel in biofuel plants, thereby improving the energy balance of these production systems.

Based on current technology used in Europe, almost half of the energy used in the production of bioethanol from wheat is the energy needed in the drying process of the distiller's waste [16]. When the distiller's waste is digested and used for biogas production, the drying process becomes redundant, saving a large amount of energy. The total energy input in the ethanol production will therefore be reduced if the distiller's waste is digested for biogas production. At the same time, the output of vehicle fuels (ethanol and biogas) measured per hectare of arable land will increase compared with ethanol production alone. However, a prerequisite for the success of this bio-refinery concept is that the use of the digestate as fertilizer is efficient with regard to transportation and spreading operations. Large-scale, combined bioethanol and biogas plants will generate significant amounts of wet digestate that will require large storage capacities and areas of arable land located close to the plant to avoid long transportation distances [10]. Alternative options are the development of new and energy-efficient technologies for the treatment of the digestate that could separate the digestate into a solid and a liquid phase from which nutrients could be recovered.

## Mitigation of greenhouse gas emission

Substituting biofuels for fossil fuels used in vehicles will lead to a reduction in greenhouse gas emissions. However, biofuels produced from energy crops are not greenhouse-gas neutral because fossil fuels are used in the cultivation of energy crops, causing carbon dioxide emissions. Examples are diesel fuel used by tractors and natural gas used in the production of chemical fertilizers. Energy crop production often uses large amounts of fertilizers. The production of chemical fertilizers also causes emissions of nitrous gas ($N_2O$), which is 300-fold more potent than carbon dioxide in terms of its greenhouse effect [17]. In

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[*] Gnansounou, E. and Dauriat, A. (2005) Energy balance of bioethanol: a synthesis. Paper presented at the 14th European Biomass Conference and Exhibition, 17–21 October, Paris, France.

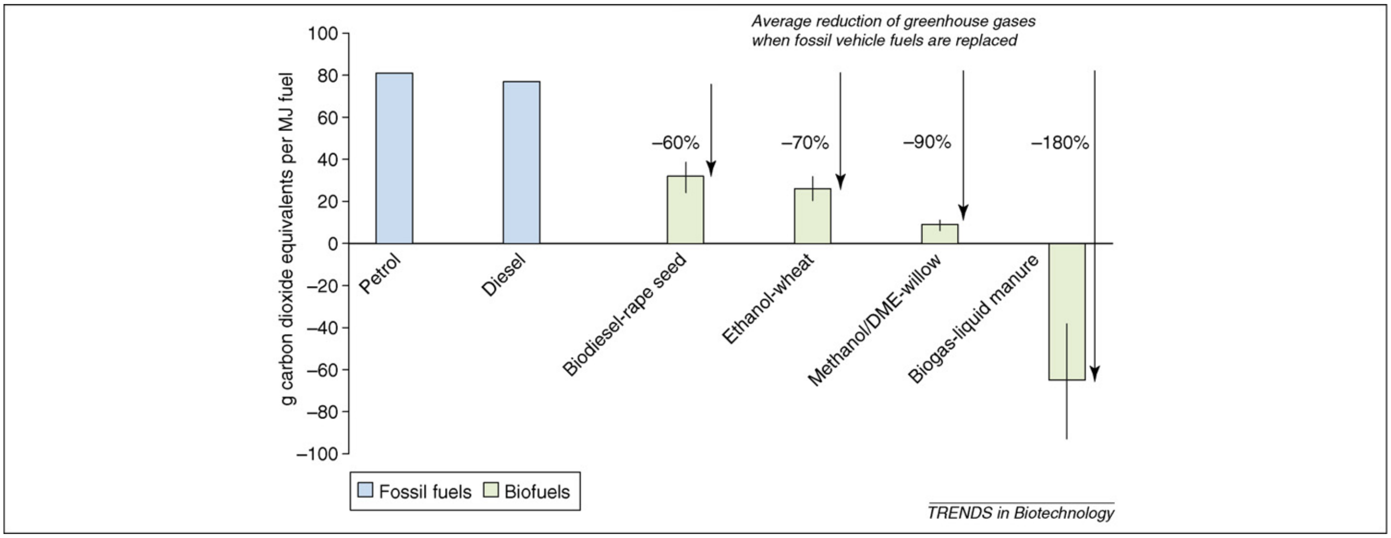

**Figure 3**. Average life-cycle emissions of greenhouse gases from fossil fuels for vehicles and biofuels based on current production conditions in Sweden. The different energy crops were cultivated in southern Sweden on average agricultural land and biofuel plants used biomass-based electricity and heat. The arrows illustrate the size of the average reduction of greenhouse gases (%) when the biofuels are replacing diesel or petrol. The biogenic emissions of greenhouse gases from the production of biofuels (e.g. emissions of nitrous oxide from the soil in energy crop cultivation and emissions of methane from conventional storage of liquid manure) might vary significantly depending on local conditions. This variation was estimated to affect the total life-cycle emissions of greenhouse gases by up to +/− 20% for biodiesel, ethanol and methanol or DME, and by up to +/− 40% concerning biogas, respectively. Data are taken from Refs [5,6,10,11,15].

addition, depending on the soil conditions, the spreading of nitrogen fertilizers might lead to biogenic $N_2O$ emissions [18,19]. From the perspective of greenhouse-gas emissions, the emissions of nitrous oxide from the production and use of nitrogen fertilizers will often exceed the emissions of carbon dioxide from the use of fossil fuels in the cultivation of energy crops [5,6,15,20].

Figure 3 shows the average life-cycle emissions of greenhouse gases for various vehicle fuels, based on current Swedish conditions and expressed as carbon dioxide equivalents. When diesel is replaced by biodiesel from rape seed, the reduction of greenhouse gases is estimated to be 60% on average [10]. Corresponding values for the reduction of $CO_2$ equivalents for bioethanol and methanol and/or DME are estimated to be 70% and 90% on average, respectively. These results are consistent with similar previous studies, such as the European ‘well-to-wheel’ study by Concawe *et al.* [11]. Currently, heat and electricity used in Swedish bioethanol and biodiesel plants are usually generated from renewable sources, thereby not producing additional greenhouse gases (e.g. wood chips from forest logging residues). However, in other European countries and in North America, bioethanol and biodiesel plants are commonly fuelled by oil, coal or natural gas and this in turn leads to an increased life-cycle emission of greenhouse gases associated with these biofuels [11]. Consequently, this reduces the benefits of these biofuels for reducing greenhouse gas emission by replacing diesel and petrol.

From a greenhouse-gas perspective, the production of biogas from liquid manure is particularly favourable owing to its associated dual greenhouse-gas benefit, that is, the reduction in the emission of methane and the reduction of the release of carbon dioxide from fossil fuels. Storage of liquid manure leads to spontaneous emissions of methane, which is a 20-fold more potent greenhouse gas than carbon dioxide [17]. Methane emissions will be significantly reduced if the manure is digested in biogas production systems and, if calculated as carbon dioxide equivalents, the reduction levels could be of the same magnitude as the reduction of carbon dioxide emission if biogas replaced fossil vehicle fuels [21]. Expressed per MJ (see Table 1) of vehicle fuel, the total reduction of greenhouse gases could in theory amount to 180% [11,15], with a possible variation of 40% [15,22]. This variation is due to the fact that the reduction of biogenic greenhouse gases, such as methane emitted from manure and nitrous oxide emitted from the soil, might vary significantly depending on local conditions [18,19,21]. The estimates for life-cycle emissions of biodiesel, ethanol and methanol and/or DME are estimated to vary by ~20% [5,6,10,22]. The main reason why the variation is higher for biogas based on manure compared with the other biofuels is that the emissions of methane represent a higher share of the total greenhouse gases related to biogas than the share of nitrous oxide emissions related to energy crop production and consequently to the biofuels based on these crops.

## Environmental effects other than greenhouse gases

An introduction of biogas systems might also lead to indirect environmental effects that are not direct results of the replacement of other energy systems. Such indirect effects are seldom considered in environmental analyses of biogas systems, although they can affect the results significantly [15]. One example that is shown in Figure 3 (discussed in earlier section) was reduced emission of methane from storage of liquid manure if the manure is used for biogas production. Another example is the anaerobic digestion and subsequent biogas production from organic waste materials that are otherwise composted. Composting of organic waste causes biological emissions of ammonia, nitrous oxide and methane and these emissions can be significant if gas-cleaning equipment is not used. Thus, the digesting of organic waste produces indirect environmental benefits, in the form of reduced emissions of greenhouse gases (methane and nitrous oxide) and pollutants contributing to eutrophication (ammonia), and these indirect effects might even exceed the direct environmental benefits of replacing fossil vehicle fuels with biogas [15]. Another important advantage of biogas technology is its application in the treatment of municipal solid waste with a concomitant reduction in the waste volume. This is an important issue, particularly in countries with high population densities and the associated large landfill sites.

The collection of surplus biomass from agricultural byproducts such as crop residues for biogas production has the additional advantage of reduced leakage of nutrients into the environment during the non-cropping season. For example, a 100 hectare farm in northern Europe might leak up to 3 tonnes of nitrogen annually if crop residues, such as tops and leaves from sugar beets, are left in the field [15]. Nitrogen leaching, which might contribute to eutrophication, will be dramatically reduced if crop residues are used for biogas production. Furthermore, recycling of nutrients such as nitrogen reduces the need for fertilizer and this will also contribute positively to the net energy balance because the production of nitrogen fertilizer is an energy-consuming process. It has been estimated that this indirect energy saving might correspond to almost 10% of the energy content in the biogas product [12]. In addition, reduced production of nitrogen fertilizer will also lead to reduced emissions of two greenhouse gases – carbon dioxide generated from the energy input in the production plant (mainly natural gas) and nitrous oxide from the production process, as discussed previously.

## Discussion

Currently, ambitious policy incentives for an increase in the use of renewable fuels, such as biofuels for the transport sector, are leading to a rapid increase in the production and consumption of bioethanol and biodiesel. Current commercial conversion technologies with their existing infrastructure for distribution, as well as current vehicle technologies, favour these types of biofuels and their competitiveness has increased with an increase in the price of crude oil. According to the International Energy Agency, without any government support measures, ethanol from sugar cane can compete with oil-based fuel at a crude oil price of ~USD 40–50 per bbl (barrel, equivalent to 159 $dm^3$), and with biodiesel from animal fats at a price of ~USD 60–70 per bbl [23]. Based on current production technologies, other biofuels will only be competitive when the crude oil price is well above USD 70 per bbl. Commercial bioethanol production costs, without considering any agricultural subsidies, direct grants or other governmental incentives, currently range from USD 0.25–0.50 per litre of petrol equivalent for sugar cane-based ethanol in Brazil, and from USD 0.70–0.95 for wheat-based ethanol in Western Europe. Corresponding costs for biodiesel from animal fats range from USD 0.40–0.55 per litre of petrol equivalent, and from USD 0.70–1.0 for biodiesel based on vegetable oils (rape seed in Europe, soybean in the USA and palm oil in Malaysia) [23].

To make biogas a viable and competitive alternative for vehicle fuel under current conditions, its price needs to be 20–30% lower than the price of bioethanol and biodiesel, owing to the additional costs of adapting cars to biogas (in so-called 'bi-fuel' cars, which run on both biogas and petrol) [9]. For standard passenger cars, this additional cost is ~10%, leading to a 10% higher price for a bi-fuel car than for an equivalent petrol-fuelled car, whereas the extra costs for passenger cars adapted for bioethanol and biodiesel are almost insignificant. Another barrier to the use of biogas is the limited number of gas filling stations, and improving the infrastructure will require further investment. Based on current technology, commercial biogas production costs, including upgrading and pressurization, might range from USD 0.45–0.55 per litre of petrol equivalent, if liquid manure and organic waste are used as feedstock [10]. If energy crops are used as feedstock, the production cost of biogas as vehicle fuel might increase up to USD 0.80 per litre of petrol equivalent, not taking any government support measures into account. Thus, the competitiveness of biogas as a vehicle fuel is currently limited compared with the most cost-efficient production systems of ethanol and biodiesel, particularly for biogas systems that are based on energy crops. However, compared with wheat-based ethanol production, biogas production systems that are based on organic waste and liquid manure could already be competitive at this point in time, even when the effects of various government interventions are excluded.

From a resource- and energy-efficiency point of view, current bioethanol and biodiesel production systems have limitations. By calculating the amount of agricultural land needed for the production of ethanol and biodiesel, it becomes apparent that only a minor part of fossil fuels currently used in vehicles could be replaced by biofuels. For example, the OECD (Organization for Economic Co-operation and Development) estimated that 30 to 60% of today's agricultural land in the USA, Canada and the EU was needed to replace 10% of fossil fuels consumption for vehicles alone [24]. Thus, new and more-efficient production systems for alternative biofuels are needed, together with more-efficient vehicle technologies, such as hybrid cars. Examples of more-efficient biofuel production systems are those based on lignocellulose feedstock and thermal gasification. Another complementary approach is the production of biogas for use as a vehicle fuel from organic wastes and byproducts in agriculture and associated industries, preferably in co-digestion with energy crops. Compared with bioethanol from wheat and biodiesel from rape seed, biogas production based on energy crops could generate about twice the net energy yield per hectare per year.

Furthermore, biogas production could be used for improving the resource efficiency of current production methods for bioethanol and biodiesel, using the byproducts generated by these methods. Thus, biogas production systems have the potential to be integrated in various existing bio-refinery models. Another important benefit of biogas systems is their ability to contribute to the reduction of greenhouse gases, particularly when liquid manure is used as the source material. However, a prerequisite is that uncontrolled loss of methane from both anaerobic digestion and the required upgrading process (i.e. removal of carbon dioxide so that the methane content exceeds 96%) are low, at less than a few percent [15,22]. Therefore, special attention should be paid to the development of optimized biogas production processes that will result in minimal losses of methane.

The resource and environmental benefits of efficient biogas systems are seldom reflected in the economics of these systems. To date, only a few types of biogas systems produce competitive vehicle fuels, such as systems partly based on food industry waste, which is charged for, whereas the majority of biogas systems need further incentives to reach profitability [9]. The main advantage of biogas is its flexibility – it can be produced from a wide range of raw materials and used in various energy services. However, this also makes biogas systems receptive to several different incentives and barriers, including energy, environmental, waste treatment and agricultural policies. Because of the complexity of the biogas systems and the many actors involved, all pursuing their own interests, the process of implementing adequate policy instruments requires concerted efforts.

## Future prospects

The examples presented here are based on current technologies. It is, however, important to consider technologies that are under development and to extrapolate the effects predicted in such studies. For example, in the production of bioethanol from cellulose the enzymatic hydrolysis of cellulose has long been a limiting factor. Recently, steam pretreatment has been used to open up the cellular structure, therefore making it accessible to the hydrolysing enzymes [25–27]. Furthermore, through massive programmes sponsored by the Department of Energy (DOE) in the USA, the costs for hydrolytic enzymes are expected to be dramatically reduced. In the future, these factors will facilitate the development of efficient processes for hydrolysing cellulose and for converting the sugars to ethanol. Possible future production costs of bioethanol from lignocellulose are estimated to range from USD 0.23–0.65 per litre of petrol equivalent, thus making it comparable to the costs of bioethanol from sugar cane [23]. Compared with ethanol from lignocellulose, the future production costs of lignocellulose-based biofuels produced by thermal gasification are estimated to be ~10–20% higher for methanol and DME, and 15–25% higher for FT diesel [11].

The process of biodiesel production is relatively simple. Hydrolysis and esterification are catalysed by inorganic catalysts (bases). These might cause environmental problems and current studies are addressing the possibility of replacing the bases with enzymes [28,29]. Although technically viable, the economic value of this approach is still somewhat uncertain because there is limited experience of this approach in commercial production. However, technological advances and larger scale plants are estimated to lower production costs of biodiesel from vegetable oils to USD 0.40–0.75 per litre of petrol equivalent by 2030 [23].

The biogas process is the most complicated of the three biotechnological processes (Box 1). A complex consortium of microorganisms catalyses the degradation of complex organic molecules, which results in the production of methane and carbon dioxide as well as some heat. This process remains technically underdeveloped and several crucial aspects need to be addressed. The volumetric productivities need to be raised substantially and the conversion rate of generated digestate improved to reduce the volume of biofertilizer generated. Overcoming these limitations will result in the production of increased amounts of gas, while generating less biofertilizer with a higher nutrient content. The volumetric productivities of processing the biomass feedstock to the final biofuels will strongly influence the investments needed to make the technology commercially viable.

### Box 1. The biogas process

Conversion of biomass to biogas is catalysed by a complex mixture of microorganisms, each having a different role in the process:

- Hydrolysis: degradation of complex organic macromolecules into monomers
- Acidogenesis: conversion of soluble monomers into volatile fatty acids
- Acetogenesis: production of acetic acid
- Methanogenesis: conversion of acetic acid or hydrogen and carbon dioxide into methane.

When dealing with solid and particulate material it is often the hydrolysis step that is rate-limiting. However, when easily degradable material is present or when soluble monomers are available, enrichment of acids might take place because methanogenesis becomes the rate-limiting step.

Processes producing ethanol and biogas are product-inhibited – in the case of ethanol by the end product, and for biogas by volatile fatty acids that are generated as metabolic intermediates [30]. Ethanol in concentrations above a certain threshold will drastically reduce the fermentative capacity of the organisms used. In the case of biogas, an enrichment of volatile fatty acids in the reactor might stop the process altogether [31,32]. It is therefore important to develop sufficient monitoring and control strategies [33,34] in addition to adapting the biology of the catalysing organisms (e.g. by genetically engineering). Another viable option is to integrate a product-recovery step into the production process [30]. Taken together, these factors mean there is significant potential for improving the process of biogas production, which will also lead to considerable cost reductions. Future production costs for upgrading biogas for use in vehicle fuel are estimated to be similar to those for lignocellulose-based vehicle fuels, such as ethanol, methanol and DME, if manure and organic waste products are used as feedstock in biogas production [30]. The use of energy crops as feedstock for biogas production will result in higher production costs owing to intrinsic costs of crop production.

This paper is written mainly from the European perspective of crop production. Crop production is different in other parts of the world, such as Brazil and the USA, which have thriving biofuel industries and biofuels are generated in these areas with different productivities. However, to evaluate biofuel processes on a global scale it would be useful to conduct similar analyses to those presented here. There is currently a consensus that more biofuels should be used in the transport sector and it is therefore important to analyse environmental effects, demands on agricultural land and also possibilities to improve the technology for the production processes. How this is done will be of utmost importance for the future.

## Conclusions

In the future there will be an increased demand for land for the production of biomass for food and animal feed, chemicals, materials and energy. Therefore, it is important to prioritize processes, production systems and products that are efficient with regard to the land area used and the use of organic byproducts and wastes, and also according to their environmental impact, particularly in terms of reduction of greenhouse gas emission. Based on these criteria, biogas vehicle fuel stands out as a promising alternative, together with the 'second generation' vehicle fuels that are based on lignocellulose. Compared to the majority of the liquid biofuels in use today, biogas often has a far better performance with regard to both area efficiency and life cycle emissions, and it is therefore a strong potential candidate for becoming one of the most sustainable vehicle fuels in the near future.

### Acknowledgements

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