Chapter 7
Biofuel conversion technologies

Andre Faaij

1. Introduction

In the current heated societal debate about the sustainability of biofuels, usually a distinction is made between so-called 'first' and 'second' generation biofuels. A large number of options to produce biomass from biofuel is used or are possible (a simplified overview of options is given in Figure 1). Although definitions differ between publications, first generation biofuels typically are produced from food crops as oilseeds (rapeseed, palm oil), starch crops (cereals, maize) or sugar crops (sugar beet and sugarcane). Conversion technologies are commercial and typically feedstock costs dominate the overall biofuel production costs. Furthermore,

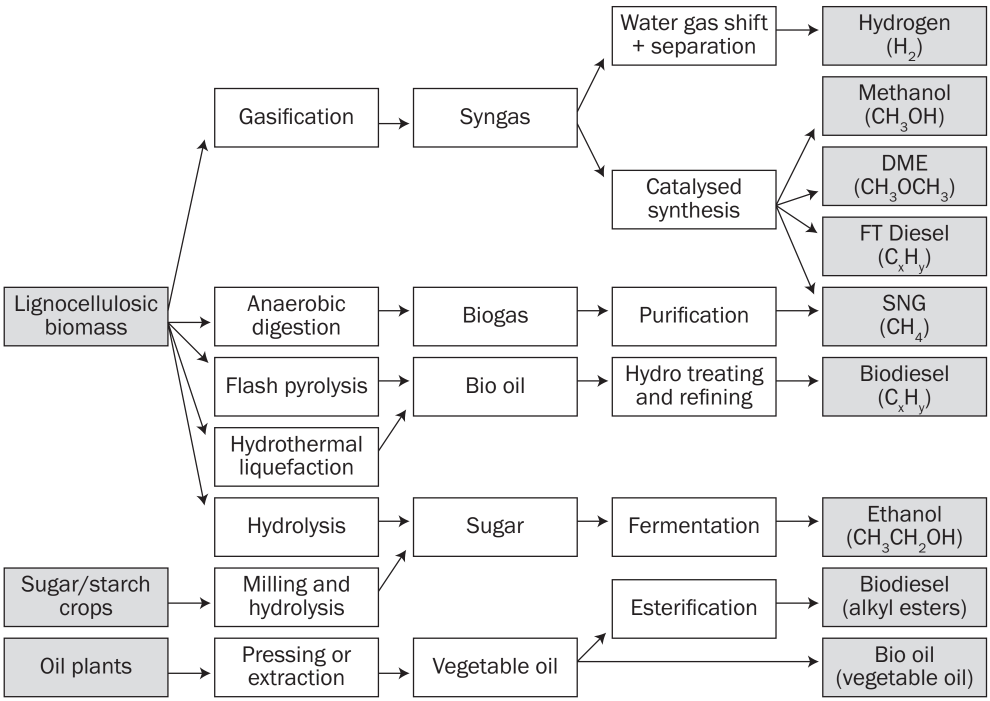

Figure 1. different existing and possible biofuel production routes (Hamelinck and Faaij, 2006). This is a simplified overview; other production chains are possible for example by combining conversion pathways, e.g. combined ethanol and biogas production, ethanol production and gasification of lignine for synfuels and integrated concepts with other industrial processes (pulp & paper plants) or bio refineries.

in particular when food crops are used grown in temperate climates (i.e. the US and the EU), costs are typically high due to high feedstock costs and the net overall avoided GHG emissions range between 20-50% compared to conventional gasoline or diesel (Fulton, 2004, Hunt *et al.*, 2007). Another constraint is that such food crops need to be produced on better quality land and increased demand directly competes with food markets. This has recently led to a wide range of estimates on the presumed impact of biofuel production on food prices (FAO, 2008), ranging between 3 up to 75%. However, sugarcane based ethanol production is a notable exception to these key concerns. Overall production costs as achieved in Brazil are competitive without subsidies, net GHG balance achieves 80-90% reduction and sugar prices have remained constant or have decreased slightly over the past years, despite strong increases in ethanol production from sugarcane.

Palm oil, in turn, although far less important as feedstock for biofuel production has been at the centre of the sustainability debate, because it's production is directly linked to loss of rainforest and peat lands in South-East Asia. Nevertheless, palm oil is an efficient and high yield crop to produce vegetal oil (Fulton, 2004). Recently, interest in Jatropha, a oil crop that can be grown in semi-arid conditions is growing, but commercial experience is very limited to date.

Second generation biofuels are not commercially produced at this stage, although in various countries demonstration projects are ongoing. 2nd generation biofuels are to be produced from lignocellulosic biomass. In lignocellulose, typically translated as biomass from woody crops or grasses and residue materials such as straw, sugars are chemically bound in chains and cannot be fermented by conventional micro-organisms used for production of ethanol from sugars and the type of sugars are different than from starch or sugar crops. In addition, woody biomass contains (variable) shares of lignine, that cannot be converted to sugars. Thus, more complex conversion technology is needed for ethanol production. Typical processes developed include advanced pre-treatment and enzymatic hydrolysis, to release individual sugars. Also fermentation of C5 instead of C6 sugars is required. The other key route being developed is gasification of lignocellulosic biomass, subsequent production of clean syngas that can be used to produce a range of synthetic biofuels, including methanol. DME and synthetic hydrocarbons (diesel). Because lignocellulosic biomass can origin from residue streams and organic wastes (that do in principle not lead to extra land-use when utilised), from trees and grasses that can also be grown on lower quality land (including degraded and marginal lands), it is thought that the overall potential of such routes is considerably larger on longer term than for 1st generation biofuels. Also, the inherently more extensive cultivation methods lead to very good net GHG balances (around 90% net avoided emissions) and ultimatly, they are thought to deliver competitive biofuels, due to lower feedstock costs, high overall chain efficiency, net energy yield per hectare, assuming large scale conversion.

This chapter gives an overview of the options to produce fuels from biomass, addressing current performance and the possible technologies and respective performance levels on longer term. It focuses on the main currently deployed routes to produce biofuels and on the key chains that are currently pursued for production of 2nd generation biofuels. Furthermore, an outlook on future biomass supplies is described in section 2, including a discussion of the impact of sustainability criteria and main determining factors and uncertainties. The chapter is finalized with a discussion of projections of the possible longer term role of biofuels on a global scale and the respective contribution of first and second generation biofuels.

2. Long term potential for biomass resources.

This section discusses a integral long term outlook on the potential global biomass resource base, including the recent sustainability debate and concerns. This assessment covered on global biomass potential estimates, focusing on the various factors affecting these potentials, such as food supplies, water use, biodiversity, energy demands and agro-economics (Dornburg *et al.*, 2008). The assessment focused on the relation between estimated biomass potentials and the availability and demand of water, the production and demand of food, the demand for energy and the influence on biodiversity and economic mechanisms.

The biomass potential, taken into account the various uncertainties as analysed in this study, consists of three main categories of biomass:

1. *Residues* from forestry and agriculture and organic waste, which in total represent between 40 - 170 EJ/yr, with a mean estimate of around 100 EJ/yr. This part of the potential biomass supplies is relatively certain, although competing applications may push the net availability for energy applications to the lower end of the range. The latter needs to be better understood, e.g. by means of improved models including economics of such applications.
2. *Surplus forestry*, i.e. apart from forestry residues an additional amount about 60-100 EJ/yr of surplus forest growth is likely to be available.
3. Biomass produced via *cropping systems*:
   a. A lower estimate for energy crop production *on possible surplus good quality agricultural and pasture lands*, including far reaching corrections for water scarcity, land degradation and new land claims for nature reserves represents an estimated 120 EJ/yr ('*with exclusion of areas*' in Figure 2).
   b. The potential contribution of *water scarce, marginal and degraded lands* for energy crop production, could amount up to an additional 70 EJ/yr. This would comprise a large area where water scarcity provides limitations and soil degradation is more severe and excludes current nature protection areas from biomass production ('*no exclusion*' in Figure 2).
   c. *Learning in agricultural technology* would add some 140 EJ/yr to the above mentioned potentials of energy cropping.

The three categories added together lead to a biomass supply potential of up to about 500 EJ.

Energy demand models calculating the amount of biomass used if energy demands are supplied cost-efficiently at different carbon tax regimes, estimate that in 2050 about 50-250 EJ/yr of biomass are used. At the same time, scenario analyses predict a global primary energy use of about 600 – 1040 EJ/yr in 2050 (the two right columns of Figure 2). Keep in mind that food demand of around 9 billion people in 2050 are basically met in those scenario's.

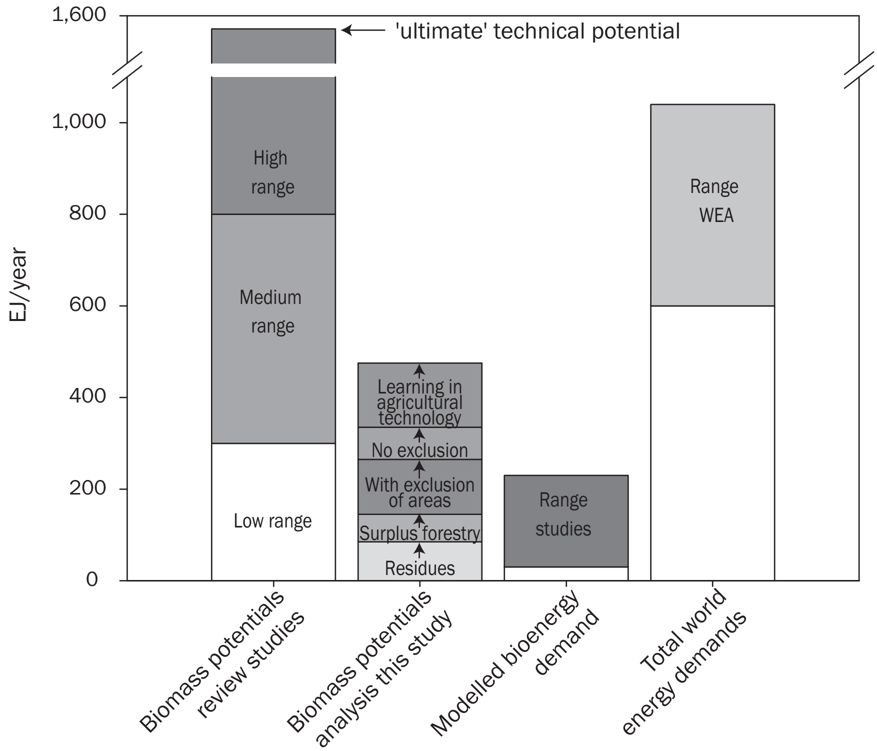

Figure 2. Comparison of biomass supply potentials in the review studies and in this study with the modelled demand for biomass and the total world energy demand, all for 2050 (Dornburg *et al.*, 2008). EJ = Exajoule (current global energy use amounts about 470 EJ at present). The first bar from the left represents the range of biomass energy potentials found in different studies, the second presents the results generated in (Dornburg *et al.*, 2008), taking a variety of sustainability criteria into account (such as water availability, biodiversity protection and soil quality), the third bar shows currently available estimates of biomass demand for energy from long term scenario studies and the fourth bar shows the range of projections of total global energy use in 2050.

In principle, biomass potentials are likely to be sufficient to allow biomass to play a significant role in the global energy supply system. Current understanding of the potential contribution of biomass to the future world energy supply is that the total technical biomass supplies could range from about 100 EJ using only residues up to an ultimate technical potential of 1500 EJ/yr potential per year. The medium range of estimates is between 300 and 800 EJ/yr (first column of Figure 2).

This study (Dornburg *et al.*, 2008) has confirmed that annual food crops may not be suited as a prime feedstock for bioenergy, both in size of potentials and in terms of meeting a wide array of sustainability criteria, even though annual crops can be a good alternative under certain circumstances. Perennial cropping systems, however, offer very different perspectives. These cannot only be grown on (surplus) agricultural and pasture lands, but also on more marginal and degraded lands, be it with lower productivity. At this stage there is still limited (commercial) experience with such systems for energy production, especially considering the more marginal and degraded lands and much more development, demonstration (supported by research) is needed to develop feasible and sustainable systems suited for very different settings around the globe. This is a prime priority for agricultural policy.

As summarized, the size of the biomass resource potentials and subsequent degree of utilisation depend on numerous factors. Part of those factors are (largely) beyond policy control. Examples are population growth and food demand. Factors that can be more strongly influenced by policy are development and commercialization of key technologies (e.g. conversion technology that makes production of fuels from lignocellulosic biomass and perennial cropping systems more competitive), e.g. by means of targeted RD&D strategies. Other areas are:

- Sustainability criteria, as currently defined by various governments and market parties.
- Regimes for trade of biomass and biofuels and adoption of sustainability criteria (typically to be addressed in the international arena, for example via the WTO).
- Infrastructure; investments in infrastructure (agriculture, transport and conversion) is still an important factor in further deployment of bioenergy.
- Modernization of agriculture; in particular in Europe, the Common Agricultural Policy and related subsidy instruments allow for targeted developments of both conventional agriculture and second generation bioenergy production. Such sustainable developments are however crucial for many developing countries and are a matter for national governments, international collaboration and various UN bodies.
- Nature conservation; policies and targets for biodiversity protection do determine to what extent nature reserves are protected and expanded and set standards for management of other lands.
- Regeneration of degraded lands (and required preconditions), is generally not attractive for market parties and requires government policies to be realized.

Current insights provide clear leads for further steps for doing so. In the criteria framework as defined currently by several governments, in roundtables and by NGO's, it is highlighted that a number of important criteria require further research and design of indicators and verification procedures. This is in particular the case for to the so-called 'macro-themes' (land-use change, biodiversity, macro-economic impacts) and some of the more complex environmental issues (such as water use and soil quality). Sustainability of biofuels and ongoing development around defining criteria and deployment of certification is discussed in Chapter 5 of this book by Neves do Amaral.

3. Technological developments in biofuel production

The previous section highlights the importance of lignocellulosic resources for achieving good environmental performance and reducing the risks of competition for land and with food production. This implies that different technologies are required to produce liquid fuels, compared to the currently dominant use of annual crops as maize and rapeseed. Sugarcane is however a notable exception given it's very high productivity, low production costs and good energy and GHG balance (Macedo *et al.*, 2004; Smeets *et al.*, 2008).

Three main routes can be distinguished to produce transportation fuels from biomass: gasification can be used to produce syngas from lignocellulosic biomass that can be converted to methanol, Fischer-Tropsch liquids, DiMethylEther (DME) and hydrogen. Production of ethanol can take place via direct fermentation of sugar and starch rich biomass, the most utilized route for production of biofuels to date, or this can be preceded by hydrolysis processes to convert lignocellulosic biomass to sugars first. Finally, biofuels can be produced via extraction from oil seeds (vegetal oil from e.g. rapeseed or palm oil), which can be esterified to produce biodiesel.

Other conversion routes and fuels are possible (such as production of butanol from sugar or starch crops) and production of biogas via fermentation. The above mentioned routes have however so far received most attention in studies and Research and Demonstration efforts.

3.1. Methanol, hydrogen and hydrocarbons via gasification

Methanol (MeOH), hydrogen (H_2) and Fischer Tropsch synthetic hydrocarbons (especially diesel), DME (DiMethylEther) and SNG (Synthetic Natural Gas) can be produced from biomass via gasification. All routes need very clean syngas before the secondary energy carrier is produced via relatively conventional gas processing methods. Here, focus lays on the first three fuels mentioned.

Several routes involving conventional, commercial, or advanced technologies under development, are possible. Figure 3 pictures a generic conversion flowsheet for this category of processes. A train of processes to convert biomass to required gas specifications precedes the methanol or FT reactor, or hydrogen separation. The gasifier produces syngas, a mixture of CO and H_2, and a few other compounds. The syngas then undergoes a series of chemical reactions. The equipment downstream of the gasifier for conversion to H_2, methanol or FT diesel is the same as that used to make these products from natural gas, except for the gas cleaning train. A gas turbine or boiler, and a steam turbine optionally employ the unconverted gas fractions for electricity co-production (Hamelinck *et al.*, 2004).

So far, commercial biofuels production via gasification does not take place, but interest is on the rise and development and demonstration efforts are ongoing in several OECD countries.

Overall energetic efficiencies of relatively 'conventional' production facilities, could be close to 60% (on a scale of about 400 MW_{th} input). Deployment on large scale (e.g over 1000 MW_{th}) is required to benefit maximally from economies of scale, which are inherent to this type of installations. Such capacities are typical for coal gasification. The use of coal gasifiers and feeding of pre-treated biomass (e.g. via torrefaction or pyrolysis oils) could prove one of the shorter term options to produce 2nd generation biofuels efficiently. This conversion route has a strong position from both efficiency and economic perspective (Hamelinck *et al.*, 2004; Hamelinck and Faaij, 2002; Tijmensen et al, 2002; Williams *et al.*, 1995). Generic performance ranges resulting from various pre-engineering studies are reported in Figure 3.

The findings of the previously published papers can be summarised as follows: gasification-based fuel production systems that apply pressurised gasifiers have higher joint fuel and electricity energy conversion efficiencies than atmospheric gasifier-based systems. The total efficiency is also higher for once-through configurations, than for recycling configurations that aim at maximising fuel output. This effect is strongest for FT production, where (costly) syngas recycling not only introduces temperature and pressure leaps, but also 'material leaps' by reforming part of the product back to syngas. For methanol and hydrogen, however,

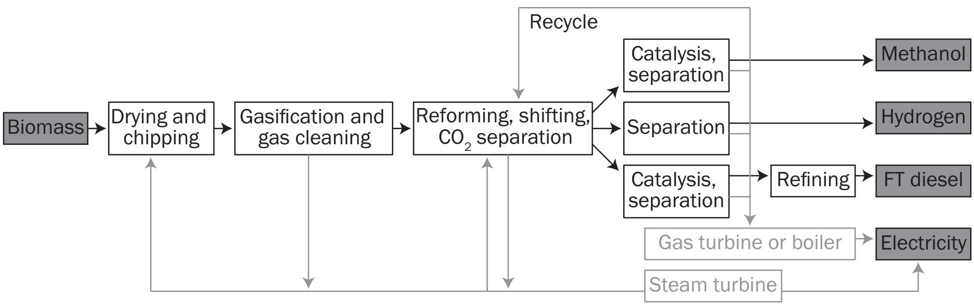

Figure 3. Generic process scheme for production of synthetic biofuels via gasification (Hamelinck and Faaij, 2006).

maximised fuel production, with little or no electricity co-production, generally performs economically somewhat better than once-through concepts.

Hot (dry) gas cleaning generally improves the total efficiency, but the economical effects are ambivalent, since the investments also increase. Similarly, CO_2 removal does increase the total efficiency (and in the FT reaction also the selectivity), but due to the accompanying increase in investment costs this does not decrease the product costs. The bulk of the capital investment is in the gasification and oxygen production system, syngas processing and power generation units. These parts of the investment especially profit from cost reductions at larger scales. Also, combinations with enriched air gasification (eliminating the expensive oxygen production assumed for some methanol and hydrogen concepts) may reduce costs further.

Several technologies considered here are not yet fully proven or commercially available. Pressurised (oxygen) gasifiers still need further development. At present, only a few pressurised gasifiers, operating at relatively small scale, have proved to be reliable. Consequently, the reliability of cost data for large-scale gasifiers is uncertain. A very critical step in all thermal systems is gas cleaning. It still has to be proven whether the (hot) gas cleaning section is able to meet the strict cleaning requirements for reforming, shift and synthesis. Liquid phase reactors (methanol and FT) are likely to have better economies of scale. The development of ceramic membrane technology is crucial to reach the projected hydrogen cost level. For FT diesel production, high CO conversion, either once through or after recycle of unconverted gas, and high C5+ selectivity are important for high overall energy efficiencies. Several units may be realised with higher efficiencies than considered in this paper: new catalysts and carrier liquids could improve liquid phase methanol single pass efficiency. At larger scales, conversion and power systems (especially the combined cycle) have higher efficiencies, further stressing the importance of achieving economies of scale for such concepts.

3.2. Production of ethanol from sugarcane

Ethanol production from sugarcane has established a strong position in Brazil and increasingly in other countries in tropical regions (such as India, China and various countries in Sub-Saharan Africa). Production costs of ethanol in Brazil have steadily declined over the past few decades and have reached a point where ethanol is competitive with production costs of gasoline (Wall-Bake *et al.*, 2008). As a result, bioethanol is no longer financially supported in Brazil and competes openly with gasoline.

Large scale production facilities, better use of bagasse and trash residues from sugarcane production e.g. with advanced (gasification based) power generation orhydrolysis techniques (see below) and further improvements in cropping systems, offer further perspectives for sugarcane based ethanol production.

Improvement options for sugarcane based ethanol production are plentiful (Damen, 2001; Groen, 1999). It is expected that the historic cost decreases and productivity increments will continue. An analysis of historic and potential future improvements in economic performance of ethanol production in Brazil (Wall Bake *et al.*, 2008) concludes that if improvements in sugarcane yield, logistics (e.g. green can harvesting techniques and utilisation of sugarcane trash), overall efficiency improvement in the sugar mills and ethanol production (e.g. by full electrification and advanced distillation technology) as well as the use of hydrolysis technology for conversion of bagasse and trash to ethanol, ethanol yields per hectare of land may even be tripled compared to current average production.

The key limitations for sugarcane production are climatic and the required availability of good quality soils with sufficient and the right rainfall patterns.

3.3. Ethanol from (ligno)-cellulosic biomass

Hydrolysis of cellulosic (e.g. straw) and lignocellulosic (woody) biomass can open the way towards low cost and efficient production of ethanol from these abundant types of biomass. The conversion is more difficult than for sugar and starch because from lignocellulosic materials, first sugars need to be produced via hydrolysis. Lignocellulosic biomass requires pretreatment by mechanical and physical actions (e.g. steam) to clean and size the biomass, and destroy its cell structure to make it more accessible to further chemical or biological treatment. Also, the lignin part of the biomass is removed, and the hemicellulose is hydrolysed (saccharified) to monomeric and oligomeric sugars. The cellulose can then be hydrolysed to glucose. Also C5 sugars are formed, which require different yeasts to be converted to ethanol. The sugars are fermented to ethanol, which is to be purified and dehydrated. Two pathways are possible towards future processes: a continuing consolidation of hydrolysis-fermentation reactions in fewer reactor vessels and with fewer micro organisms, or an optimisation of separate reactions. As only the cellulose and hemicellulose can be used in the process, the lignin is used for power production (Figure 4).

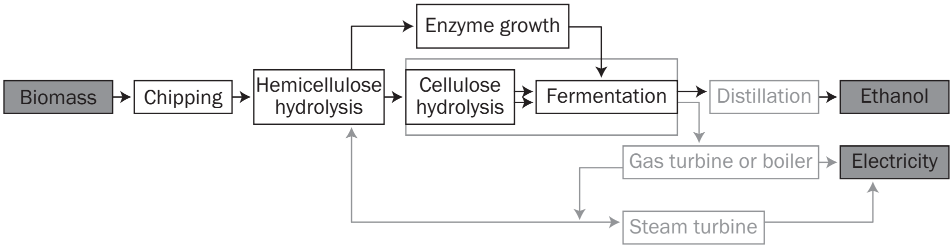

Figure 4. Generic process scheme for the production of ethanol from lignocellulosic biomass.

To date, acid treatment is an available process, which is so far relatively expensive and inefficient. Enzymatic treatment is commercially unproven but various test facilities have been built in North America and Sweden. The development of various hydrolysis techniques has gained major attention over the past 10 years or so, particularly in Sweden and the United States. Because breakthroughs seem to be necessary on a rather fundamental level, it is relatively uncertain how fast attractive performance levels can be achieved (Hamelinck *et al.*, 2005).

Assuming, however, that mentioned issues are resolved and ethanol production is combined with efficient electricity production from unconverted wood fractions (lignine in particular), ethanol costs could come close to current gasoline prices (Lynd *et al.*, 2005): as low as 12 Euroct/litre assuming biomass costs of about 2 Euro/GJ. Overall system efficiencies (fuel + power output) could go up to about 70% (LHV).

It should be noted though that the assumed conversion extent of (hemi)cellulose to ethanol by hydrolysis fermentation is close to the stoichiometric maximum. There is only little residual material (mainly lignin), while the steam demand for the chosen concepts is high. This makes the application of BIG/CC unattractive at 400MWHHV. Developments of pre-treatment methods and the gradual ongoing reactor integration are independent trends and it is plausible that at least some of the improved performance will be realised in the medium-term. The projected long-term performance depends on development of technologies that have not yet passed laboratory stage, and that may be commercially available earlier or later than 20 years from now. This would mean either a more attractive ethanol product cost in the medium-term, or a less attractive cost in the long-term. The investment costs for advanced hemicellulose hydrolysis methods is still uncertain. Continuing development of new micro-organisms is required to ensure fermentation of xylose and arabinose, and decrease the cellulase enzyme costs.

The hydrolysis technology can also boost the competitiveness of existing production facilities (e.g. by converting available crop and process residues), which provides an important market niche on short term.

Table 1. gives an overview of estimates for costs of various fuels that can be produced from biomass (Faaij, 2006). A distinction is made between performance levels on the short and on the longer term. Generally spoken, the economy of 'traditional' fuels like Rapeseed MethylEsther and ethanol from starch and sugar crops in moderate climate zones is poor at present and unlikely to reach competitive price levels in the longer term. Also, the environmental impacts of growing annual crops are not as good as perennials because per unit of product considerable higher inputs of fertilizers and agrochemicals are needed. In addition, annual crops on average need better quality land than perennials to achieve good productivities.

Production of methanol (and DME), hydrogen, Fischer-Tropsch liquids and ethanol produced from lignocellulosic biomass that offer good perspectives and competitive fuel prices in the longer term (e.g. around 2020). Partly, this is because of the inherent lower feedstock prices and versatility of producing lignocellulosic biomass under varying circumstances. Section 2 highlighted that a combination of biomass residues and perennial cropping systems on both marginal and better quality lands could supply a few hundred EJ by mid-century in a competitive cost range between 1-2 Euro/GJ (see also Hoogwijk *et al.*, 2005, 2008). Furthermore, as discussed in this paper, the (advanced) gasification and hydrolysis technologies under development have the inherent improvement potential for efficient and competitive production of fuels (sometimes combined with co-production of electricity).

Inherent to the advanced conversion concepts, it is relatively easy to capture (and subsequently store) a significant part of the CO_2 produced during conversion at relatively low additional costs. This is possible for ethanol production (where partially pure CO_2 is produced) and for gasification concepts. Production of syngas (both for power generation and for fuels) in general allows for CO_2 removal prior to further conversion. For FT production about half of the carbon in the original feedstock (coal, biomass) can be captured prior to the conversion of syngas to FT-fuels. This possibility allows for carbon neutral fuel production when mixtures of fossil fuels and biomass are used and negative emissions when biomass is the dominant or sole feedstock. Flexible new conversion capacity will allow for multiple feedstock and multiple output facilities, which can simultaneously achieve low, zero or even negative carbon emissions. Such flexibility may prove to be essential in a complex transition phase of shifting from large scale fossil fuel use to a major share of renewables and in particular biomass.

At the moment major efforts are ongoing to demonstrate various technology concepts discussed above. Especially in the US (but also in Europe), a number of large demonstration efforts is ongoing on production of ethanol from lignocellulosic biomass. IOGEN, a Canadian company working on enzymatic hydrolysis reported the production of 100,000 litres of ethanol from agricultural residues in September 2008. Also companies in India, China and Japan are investing substantially in this technology area.

Gasification for production of synfuels gets support in the US and more heavily in the EU. The development trajectory of the German company CHOREN (focusing on dedicated biomass gasification systems for production of FT liquids) is ongoing and stands in the international spotlights. Finland and Sweden have substantial development efforts ongoing, partly aiming for integration gasification technology for synfuels in the paper & pulp industry. Furthermore, co-gasification of biomass in (existing) coal gasifiers is an important possibility. This has for example been demonstrated in the Buggenum coal gasifiier in the Netherlands and currently production of synfuels is targeted.

Table 1. Performance levels for different biofuels production routes (Faaij, 2006).

Concept	Energy efficiency (HHV) + energy inputs	
	Short term	**Long term**
Hydrogen: via biomass gasification and subsequent syngas processing. Combined fuel and power production possible; for production of liquid hydrogen additional electricity use should be taken into account.	60% (fuel only) (+ 0.19 GJe/GJ H2 for liquid hydrogen)	55% (fuel) 6% (power) (+ 0.19 GJe/GJ H2 for liquid hydrogen)
Methanol: via biomass gasification and subsequent syngas processing. Combined fuel and power production possible	55% (fuel only)	48% (fuel) 12% (power)
Fischer-Tropsch liquids: via biomass gasification and subsequent syngas processing. Combined fuel and power production possible	45% (fuel only)	45% (fuel) 10% (power
Ethanol from wood: production takes place via hydrolysis techniques and subsequent fermentation and includes integrated electricity production of unprocessed components.	46% (fuel) 4% (power)	53% (fuel) 8% (power)
Ethanol from beet sugar: production via fermentation; some additional energy inputs are needed for distillation.	43% (fuel only) 0.065 GJe + 0.24 GJth/GJ EtOH	43% (fuel only) 0.035 GJe + 0.18 GJth/GJ EtOH
Ethanol from sugarcane: production via cane crushing and fermentation and power generation from the bagasse. Mill size, advanced power generation and optimised energy efficiency and distillation can reduce costs further on longer term.	85 litre EtOH per tonne of wet cane, generally energy neutral with respect to power and heat	95 litre EtOH per tonne of wet cane. Electricity surpluses depend on plant lay-out and power generation technology.
Biodiesel RME: takes places via extraction (pressing) and subsequent esterification. Methanol is an energy input. For the total system it is assumed that surpluses of straw are used for power production.	88%; 0.01 GJe + 0.04 GJ MeOH per GJ output Efficiency power generation on shorter term: 45%, on longer term: 55%	

Assumed biomass price of clean wood: 2 Euro/GJ. RME cost figures varied from 20 Euro/GJ (short term) to 12 Euro/GJ (longer term), for sugar beet a range of 12 to 8 Euro/GJ is assumed. All figures exclude distribution of the fuels to fueling stations.
For equipment costs, an interest rate of 10%, economic lifetime of 15 years is assumed. Capacities of conversion unit are normalized on 400 MWth input on shorter term and 1000 MWth input on longer term.

Investment costs (Euro/kWth input capacity)		O&M (% of inv.)	Estimated production costs (Euro/GJ fuel)	
Short term	**Long term**		**Shorter term**	**Longer term**
480 (+ 48 for liquefying)	360 (+ 33 for liquefying)	4	9-12	4-8
690	530	4	10-15	6-8
720	540	4	12-17	7-9
350	180	6	12-17	5-7
290	170	5	25-35	20-30
100 (wide range applied depending on scale and technology applied)	230 (higher costs due to more advanced equipment)	2	8-12	7-8
150 (+ 450 for power generation from straw)	110 (+ 250 for power generation from straw)	5 4	25-40	20-30

Industrial interest in those areas comes from the energy sector, biotechnology as well as chemical industry. Given the policy targets on (second generation) biofuels in North America and the EU, high oil prices and increased pressure to secure sustainable production of biofuels (e.g. avoiding conflicts with food production and achieve high reduction in GHG emissions), pressure on both the market and policy to commercialize those technologies is high. When turn-key processes are available is still uncertain, but such breakthroughs may be possible already around 2010.

4. Energy and greenhouse gas balances of biofuels

4.1. Energy yields

The energy yield per unit of land surfaces resources depends to a large extent on the crop choice and the efficiency of the entire energy conversion route from 'crop to drop'. This is illustrated by the figures in Table 2. It is important to stress that when lignocellulose is the feedstock of choice production is not constrained to arable land, but amounts to the sum of residues and production from degraded/marginal lands not used for current food production. Ultimately, this will be the preferred option in most cases.

Table 2. Indicative ranges for biomass yield and subsequent fuel production per hectare per year for different cropping systems in different settings. Starch and sugar crops assume conversion via fermentation to ethanol and oil crops to biodiesel via esterification (commercial technology at present). The woody and grass crops require either hydrolysis technology followed by ethanol or gasification to syngas to produce synthetic fuel (both not yet commercial conversion routes).

Crop	Biomass yield (odt/ha/yr)	Energy yield in fuel (GJ/ha/yr)
Wheat	4-5	~50
Maize	5-6	~60
Sugar beet	9-10	~110
Soy bean	1-2	~20
Sugarcane	5-20	~180
Palm oil	10-15	~160
Jathropha	5-6	~60
SRC temperate climate	10-15	100-180
SRC tropical climate	15-30	170-350
Energy grasses good conditions	10-20	170-230
Perennials marginal/degraded lands	3-10	30-120

4.2. Greenhouse gas balances

The net emissions over the full life cycle of biofuels – from changes in land use to combustion of fuels – that determine their impact on the climate. Research on net emissions is far from conclusive, and estimates vary widely. Calculations of net GHG emissions are highly sensitive to assumptions about system boundaries and key parameter values – for example, land use changes and their impacts, which inputs are included, such as energy embedded in agricultural machinery and how various factors are weighted.

The primary reasons for differing results are different assumptions made about cultivation, and conversion or valuation of co-products. (Larson, 2005), who reviewed multiple studies, found that the greatest variations in results arose from the allocation method chosen for co-products, and assumptions about N_2O emissions and soil carbon dynamics. In addition, GHG savings will vary from place to place – according to existing incentives for GHG reductions, for example. And the advantages of a few biofuels (e.g. sugarcane ethanol in Brazil) are location specific. As a result, it is difficult to compare across studies; however, despite these challenges, some of the more important studies point to several useful conclusions.

This analysis notwithstanding, the vast majority of studies have found that, even when all fossil fuel inputs throughout the life cycle are accounted for, producing and using biofuels made from current feedstock result in substantial reductions in GHG emissions relative to petroleum fuels.

In general, of all potential feedstock options, producing ethanol from maize results in the smallest decrease in overall emissions. The greatest benefit, meanwhile, comes from ethanol produced from sugarcane grown in Brazil (or from using cellulose or wood waste as feedstock). Several studies have assessed the net emissions reductions resulting from sugarcane ethanol in Brazil, and all have concluded that the benefits far exceed those from grain-based ethanol produced in Europe and the United States.

Fulton (2004) attributes the lower life-cycle climate impacts of Brazilian sugarcane ethanol to two major factors: First, cane yields are high and require relatively low inputs of fertilizer, since Brazil has better solar resources and high soil productivity. Second, almost all conversion plants use bagasse (the residue that remains after pressing the sugar juice from the cane stalk) for energy, and many recent plants use co-generation (heat and electricity), enabling them to feed electricity into the grid. As such, net fossil energy requirements are near zero, and in some cases could be below zero. (In addition, less energy is required for processing because there is no need for the extra step to break down starch into simple sugars. Because most process energy in Brazil is already renewable, this does not really play a role.)

According to Larson (2005), conventional grain- and oilseed-based biofuels can offer only modest reductions in GHG emissions. The primary reason for this is that they represent only a small portion of the above ground biomass. He estimates that, very broadly, biofuels from grains or seeds have the potential for a 20–30 percent reduction in GHG emissions per vehicle-kilometer, sugar beets can achieve reductions of 40–50 percent, and sugarcane (average in southeast Brazil) can achieve a reduction of 90 percent.

Other new technologies under development also offer the potential to dramatically increase yields per unit of land and fossil input, and further reducelife-cycle emissions. The cellulosic conversion processes for ethanol offers the greatest potential for reductions because feedstock can come from the waste of other products or from energy crops, and the remaining parts of the plant can be used for process energy.

Larson (2005) projects that future advanced cellulosic processes (to ethanol, F-T diesel, or DME) from perennial crops could bring reductions of 80–90 percent and higher. According to Fulton *et al.* (2004), net GHG emissions reductions can even exceed 100 percent if the feedstock takes up more CO_2 while it is growing than the CO_2-equivalent emissions released during its full life cycle (for example, if some of it is used as process energy to offset coal-fired power).

Typical estimates for reductions from cellulosic ethanol (most of which comes from engineering studies, as few large-scale production facilities exist to date) range from 70–90 percent relative to conventional gasoline, according to Fulton (2004), though the full range of estimates is far broader.

Figure 5 shows the range of estimated possible reductions in emissions from wastes and other next-generation feedstock relative to those from current-generation feedstock and technologies.

4.3. Chain efficiency of biofuels

When the use of such 'advanced' biofuels (especially hydrogen and methanol) in advanced hybrid or Fuel Cell Vehicles (FCV's) is considered, the overall chain ('tree - to – tyre') efficiency can drastically improve compared to current bio-diesel or maize or cereal derived ethanol powered Internal Combustion Engine Vehicles; the effective number of kilometres that can be driven per hectare of energy crops could go up with a factor of 5 (from a typical current 20,000 km/ha for a middle class vehicle run with RME up to over 100,000 km/ha for advanced ethanol in an advanced hybrid or FCV (Hamelinck and Faaij, 2002)). Note though, that the current exception to this performance is sugarcane based ethanol production; in Brazil the better plantations yield some 8,000 litre ethanol/ha*yr, or some 70,000 km/yr for a middle class vehicle at present. In the future, those figures can improve

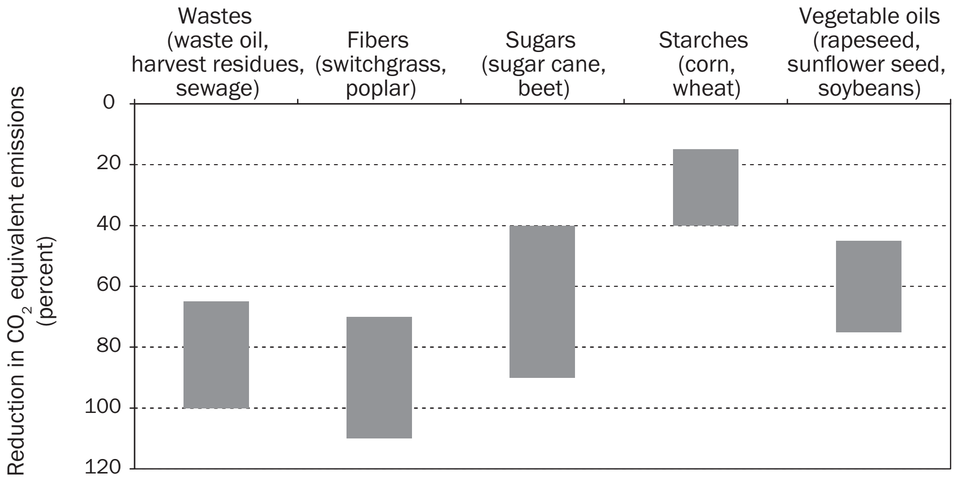

Figure 5. Reductions in greenhouse gas emissions per vehicle-kilometre, by feedstock and associated refining technology (taken from Fulton, 2004).

further due to better cane varieties, crop management and efficiency improvement in the ethanol production facilities (Damen, 2001).

Furthermore, FCV's (and to a somewhat lesser extent advanced hybrids) offer the additional and important benefits of zero or near zero emission of compounds like NO_x, CO, sulphur dioxide, hydrocarbons and small dust particulates, which are to a large extent responsible for poor air quality in many urban zones in the world. Table 3 provides a quantification of the range of kilometres that can be driven with different biofuel-vehicle combinations expressed per hectare. The ranges are caused by different yield levels for different land-types and variability and uncertainties in conversion and vehicle efficiencies. However, overall, there are profound differences between first and second generation biofuels I favour of the latter.

4.4. Future expectations on biofuels

The future biofuels and specifically the bioethanol market is uncertain. There are fundamental drivers (climate, oil prices and availability, rural development) that push for further development of biofuels. On the one hand, recent developments and public debate point towards conflicts with land use, food markets, poor GHG performance (especially when indirect land-use changes are assumed caused by biofuel production) and, even with high oil prices, high levels of subsidy for biofuels in e.g. Europe and the United States. Recently, policy targets (as discussed in chapter 5 of this book) set for biofuels are rediscussed in the EU, as well as in China. In most key markets (EU, US, China), the role of biofuels is increasingly connected to rapid deployment of 2nd generation technologies. The bulk of the growth beyond 2015 or so should be realized via such routes.

Table 3. Distance that can be driven per hectare of feedstock for several combinations of fuels and engines, derived from the net energy yield and vehicle efficiency as reported in (Hamelinck and Faaij, 2006). ICEV = Internal Combustion Engine Vehicle, FCV = Fuel Cell Vehicle.

Feedstock	Fuel	Engine	Distance (thousands km/ha)	
			Short term	Long term
Lignocellulose	Hydrogen	ICEV	26-37	80-97
		FCV	44-140	189-321
	Methanol	ICEV	34-49	75-287
		FCV	68-83	113-252
	FT	ICEV	22-38	56-167
		FCV	50-67	97-211
	Ethanol	ICEV	29-30	82-238
		FCV	38-72	129-240
Sugar beet	Ethanol	ICEV	15-37	57-88
		FCV	19-93	58-138
Rapeseed	RME	ICEV	5-28	15-79
		FCV	6-84	19-137

Some projections as published by the International Energy Agency (World Energy Outlook) and the OECD (Agricultural Outlook) focus on first generation biofuels only (even for projections to 2030 in the IEA-WEO). Biofuels meet 2.7% of world road-transport fuel demand by the end of the projection period in the Reference Scenario, up from 1% today. In the Alternative Scenario, the share reaches 4.6%, thanks to higher demand for biofuels but lower demand for road-transport fuels in total. The share remains highest in Brazil, though the pace of market penetration will be fastest in the European Union in both scenarios. The contribution of liquid biofuels to transport energy, and even more so to global energy supply, will remain limited. By 2030, liquid biofuels are projected to still supply only 3.0-3.5 percent of global transport energy demand. This is however also due to the key assumption that 2nd generation biofuel technology is not expected to become available to the market (IEA, 2006).

In the Agricultural Outlook, similar reasoning is followed be it for a shorter time frame (up to the year 2016), focusing on 1st generation biofuels. The outlook focuses in this respect on the implications of biofuel production on demand for food crops. In general, a slowdown in growth is expected (OECD, 2007).

Projections that take explicitly 2nd generation options into account are more rare, but studies that do so, come to rather different outlooks, especially in the timeframe exceeding 2020.

The IPCC, providing an assessment of studies that deal with both supply and demand of biomass and bioenergy. It is highlighted that biomass demand could lay between 70 – 130 EJ in total, subdivided between 28-43 EJ biomass input for electricity and 45-85 EJ for biofuels (Barker and Bashmakov, 2007; Kahn Ribeiro et al., 2007). Heat and biomass demand for industry are excluded in these reviews. It should also be noted that around that timeframe biomass use for electricity has become a less attractive mitigation option due to the increased competitiveness of other renewables (e.g. wind energy) and e.g. [and storage. At the same time, carbon intensity of conventional fossil transport fuels increases due to the increased use lower quality oils, tar sands and coal gasification.

In De Vries *et al.* (2007; based on the analyses of Hoogwijk *et al.* (2005, 2008)), it is indicated that the biofuel production potential around 2050 could lay between about 70 and 300 EJ fuel production capacity depending strongly on the development scenario. Around that time, biofuel production costs would largely fall in the range up to 15 U$/GJ, competitive with equivalent oil prices around 50-60 U$/barrel. This is confirmed by other by the information compiled in this chapter: it was concluded that the, sustainable, biomass resource base, without conflicting with food supplies, nature preservation and water use, could indeed be developed to a level of over 300 EJ in the first half of this century.

5. Final remarks

Biomass cannot realistically cover the whole world's future energy demand. On the other hand, the versatility of biomass with the diverse portfolio of conversion options, makes it possible to meet the demand for secondary energy carriers, as well as bio-materials. Currently, production of heat and electricity still dominate biomass use for energy. The question is therefore what the most relevant future market for biomass may be.

For avoiding CO_2 emissions, replacing coal is at present a very effective way of using biomass. For example, co-firing biomass in coal-fired power stations has a higher avoided emission per unit of biomass than when displacing diesel or gasoline with ethanol or biodiesel. However, replacing natural gas for power generation by biomass, results in levels of CO_2 mitigation similar to second generation biofuels. Net avoided GHG emissions therefore depend on the reference system and the efficiency of the biomass production and utilisation chain. In the future, using biomass for transport fuels will gradually become more attractive from a CO_2 mitigation perspective because of the lower GHG emissions for producing second generation biofuels and because electricity production on average is expected to become less carbon-intensive due to increased use of wind energy, PV and other solar-based power generation, carbon capture and storage technology, nuclear energy and fuel shift from coal to natural gas. In the shorter term however, careful strategies and policies are needed to avoid brisk allocation of biomass resources away from efficient and effective utilisation in power and heat production or in other markets, e.g. food. How this is to be done optimally will differ from country to country.

First generation biofuels in temperate regions (EU, North America) do not offer a sustainable possibility in the long term: they remain expensive compared to gasoline and diesel (even at high oil prices), are often inefficient in terms of net energy and GHG gains and have a less desirable environmental impact. Furthermore, they can only be produced on higher quality farmland in direct competition with food production. Sugarcane based ethanol production and to a certain extent palm oil and Jatropha oilseeds are notable exceptions to this given their high production efficiencies and low(er) costs.

Especially promising are the production via advanced conversion concepts biomass-derived fuels such as methanol, hydrogen, and ethanol from lignocellulosic biomass. Ethanol produced from sugarcane is already a competitive biofuel in tropical regions and further improvements are possible. Both hydrolysis-based ethanol production and production of synfuels via advanced gasification from biomass of around 2 Euro/GJ can deliver high quality fuels at a competitive price with oil down to US$55/ barrel. Net energy yields for unit of land surface are high and up to a 90% reduction in GHG emissions can be achieved. This requires a development and commercialization pathway of 10-20 years, depending very much on targeted and stable policy support and frameworks.

However, commercial deployment of these technologies does not have to be postponed for such time periods. The two key technological concepts that have shorter term opportunities (that could be seen as niches) for commercialization are:

1. Ethanol: 2nd generation can build on the 1st generation infrastructure by being built as 'add-ons' to existing factories for utilisation of crop residues. One of the best examples is the use of bagasse and trash at sugar mills that could strongly increase the ethanol output from sugarcane
2. Synfuels via gasification of biomass: can be combined with coal gasification as currently deployed for producing synfuels (such as DME, Fischer-Tropsch and Methanol) to obtain economies of scale and fuel flexibility. Carbon capture and storage can easily be deployed with minimal additional costs and energy penalties as an add-on technology.

The biomass resource base can become large enough to supply 1/3 of the total world's energy needs during this century. Although the actual role of bioenergy will depend on its competitiveness with fossil fuels and on agricultural policies worldwide, it seems realistic to expect that the current contribution of bioenergy of 40-55 EJ per year will increase considerably. A range from 200 to 400 EJ may be observed looking well into this century, making biomass a more important energy supply option than mineral oil today. Considering lignocellulosic biomass, about half of the supplies could originate from residues and biomass production from marginal/degrade lands. The other half could be produced on good quality agricultural and pasture lands without jeopardizing the worlds food supply, forests and biodiversity. The key pre-condition to achieve this goal is increased agricultural land-use efficiency, including livestock production, especially in developing regions. Improvement potentials of agriculture and livestock are substantial, but exploiting such potentials is a challenge.

References

Barker, T. and I. Bashmakov, 2007. Mitigation from a cross-sectoral perspective, In: B. Metz, O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer (eds.), Climate Change 2007: Mitigation contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge United Kingdom and New York, USA.

Damen, K., 2001. Future prospects for biofuels in Brazil - a chain analysis comparison between production of ethanol from sugarcane and methanol from eucalyptus on short and longer term in Sao Paulo State-, Department of Science, Technology & Society - Utrecht University, 70 pp.

De Vries, B.J.M., D.P. van Vuuren and M.M. Hoogwijk, 2007. Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach. Energy Policy 35: 2590-2610.

Dornburg, V., A. Faaij, H. Langeveld, G. van de Ven, F. Wester, H. van Keulen, K. van Diepen, J. Ros, D. van Vuuren, G.J. van den Born, M. van Oorschot, F. Smout, H. Aiking, M. Londo, H. Mozaffarian, K. Smekens, M. Meeusen, M. Banse, E. Lysen, and S. van Egmond, 2008. Biomass Assessment: Assessment of global biomass potentials and their links to food, water, biodiversity, energy demand and economy – Main Report, Study performed by Copernicus Institute – Utrecht University, MNP, LEI, WUR-PPS, ECN, IVM and the Utrecht Centre for Energy Research, within the framework of the Netherlands Research Programme on Scientific Assessment and Policy Analysis for Climate Change. Reportno: WAB 500102012, 85 pp. + Appendices.

Faaij, A., 2006. Modern biomass conversion technologies. Mitigation and Adaptation Strategies for Global Change 11: 335-367.

FAO, 2008. State of Food and Agriculture - Biofuels: prospects, risks and opportunities, Food and Agirculture Organisation of the United Nations, Rome, Italy.

Fulton, L., 2004. International Energy Agency, Biofuels for transport – an international perspective, Office of Energy Efficiency, Technology and R&D, OECD/IEA, Paris, France.

Groen, M., 1999. Energy rooted in sugar cubes; the interaction between energy savings and cogeneration in Indian sugar mills, Report of the Department of Science, Technology & Society – Utrecht University in collaboration with Winrock International, Utrecht, the Netherlands, pp. 34.

Hamelinck, C. and A. Faaij, 2006. Outlook for advanced biofuels. Energy Policy 34: 3268-3283.

Hamelinck, C.N. and A.P.C. Faaij, 2002. Future prospects for production of methanol and hydrogen from biomass. Journal of Power Sources 111: 1-22.

Hamelinck, C., A. Faaij, H. den Uil and H. Boerrigter, 2004. Production of FT transportation fuels from biomass; technical options, process analysis and optimisation and development potential. Energy, the International Journal 29: 1743-1771.

Hamelinck, C.N., G van Hooijdonk and A.P.C. Faaij, 2005. Future prospects for the production of ethanol from ligno-cellulosic biomass. Biomass & Bioenergy 28: 384-410.

Hoogwijk, M., A. Faaij, B. de Vries and W. Turkenburg, 2008. Global potential of biomass for energy from energy crops under four GHG emission scenarios Part B: the economic potential. Biomass & Bioenergy, in press.

Hoogwijk, M., A. Faaij, B. Eickhout, B.de Vries and W. Turkenburg, 2005. Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. Biomass & Bioenergy 29: 225-257.

Hunt, S., J. Easterly, A. Faaij, C. Flavin, L. Freimuth, U. Fritsche, M. Laser, L. Lynd, J. Moreira, S. Pacca, J.L. Sawin, L. Sorkin, P. Stair, A. Szwarc and S. Trindade, 2007. Biofuels for Transport: Global Potential and Implications for Energy and Agriculture. prepared by Worldwatch Institute, for the German Ministry of Food, Agriculture and Consumer Protection (BMELV) in coordination with the German Agency for Technical Cooperation (GTZ) and the German Agency of Renewable Resources (FNR), ISBN: 1844074226, Published by EarthScan/James & James, 336 pp.

International Energy Agency, 2006. World Energy Outlook 2006, IEA Paris, France.

Kahn Ribeiro, S., S. Kobayashi, M. Beuthe, J. Gasca, D. Greene, D.S. Lee, Y. Muromachi, P.J. Newton, S. Plotkin, D. Sperling, R. Wit and P.J. Zhou, 2007: Transport and its infrastructure. In: B. Metz, O.R. Davidson, P.R. Bosch, R. Dave and L.A. Meyer (eds.), Climate Change 2007: Mitigation contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge United Kingdom and New York, USA.

Larson, E.D., 2005. A Review of LCA Studies on Liquid Biofuel Systems for the Transport Sector. Energy for Sustainable Development 11: October 2005.

Lynd, L.R., W.H. van Zyl, J.E. McBride and M. Laser, 2005. Consolidated Bioprocessing of Lignocellulosic Biomass: An Update. Current Opinion in Biotechnology 16: 577-583.

Macedo, I.d.C., M.R.L.V. Leal and J.E.A.R. Da Silva, 2004. Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil. Secretariat of the Environment of the State of São Paulo, Brazil. Accessible at: http://www.unica.com.br/i_pages/files/pdf_ingles.pdf

OECD/FAO, 2007. Agricultural Outlook 2007-2016. Paris, France.

Smeets, E., M. Junginger, A. Faaij, A. Walter, P. Dolzan and W. Turkenburg, 2008. The sustainability of Brazilian Ethanol; an assessment of the possibilties of certified production. Biomass & Bioenergy 32: 781-813.

Tijmensen, M.J.A., A.P.C. Faaij, C.N. Hamelinck and M.R.M. van Hardeveld, 2002. Exploration of the possibilities for production of Fischer Tropsch liquids via biomass gasification. Biomass & Bioenergy 23: 129-152.

Wall-Bake, J.D., M. Junginger, A, Faaij, T. Poot and A. da Silva Walter, 2008. Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. Biomass & Bioenergy, in press.

Williams, R.H., E.D. Larson, R.E. Katofsky and J. Chen, J., 1995. Methanol and hydrogen from biomass for transportation, with comparisons to methanol and hydrogen from natural gas and coal. Centre for Energy and Environmental Studies, Princeton University, reportno. 292.