Production of advanced biofuels

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Abstract

Four promising biofuels for the future – methanol, ethanol, hydrogen, and synthetic diesel – were systematically analyzed for their technical and economic potential, and for improvements necessary to fulfil these potentials. Key technologies for the production of these fuels, such as gasification, gas processing, synthesis, hydrolysis and fermentation, and their improvement options were studied and modelled. The production facilities' technological and economic performance were analysed, applying variations in technology and scale. Production costs of these fuels range 16 – 22 €/GJ$_{HHV}$ now, down to 9 – 13 €/GJ$_{HHV}$ in future (2030) under the assumption that certain technological developments have taken place and that biomass is available at 3 €/GJ$_{HHV}$. The feedstock costs strongly influence the resulting biofuel costs by 2 – 3 €/GJ$_{fuel}$ for each €/GJ$_{HHV}$ feedstock change. In biomass producing regions such as Latin America, the four fuels could be produced at 7 – 11 €/GJ$_{HHV}$, equalling diesel and gasoline production costs. The uncertainties in the biofuels production costs of the four selected biofuels are 15 – 30 %. Large-scale gasification, thorough gas cleaning, and microbiological processes for hydrolysis and fermentation are key major fields for RD&D efforts.

La producción de biocombustibles avanzados

Se analizaron sistemáticamente, en cuanto a su potencial técnico y económico, y las mejoras necesarias para lograr dicho potencial, cuatro biocombustibles prometedores para el futuro: metanol, etanol, hidrógeno y diesel sintético. Se estudiaron y modelaron los métodos claves para la producción de dichos combustibles tales como la gasificación, el procesamiento de gas, síntesis, hidrólisis y fermentación, como también las opciones para su mejora. Se analizaron el funcionamiento técnico y económico de las instalaciones de producción, aplicando variaciones de tecnología y de escala. Suponiendo que ciertos desarrollos tecnológicos han ocurrido y que la biomasa está disponible en un valor de 3 /GJHHV, los costos de producción de dichos combustibles va de 16 – 22 /GJHHV ahora, a 9 – 13 /GJHHV en el futuro (2030). El costo de la materia prima ejerce una fuerte influencia sobre el resultante costo del biocombustible en un 2 – 3 /GJcombustible por cada /GJHHV cambio de materia prima. En regiones productoras de biomasa como Latinoamérica, los cuatro combustibles podrían producirse a un costo de 7 – 11 /GJHHV, equivalente al costo de producción de diesel y gasolina. La fluctuación en los costos de producción de los cuatro biocombustibles seleccionados es de 15 – 30 %. La gasificación a gran escala, la limpieza de gas meticulosa y los procesos microbiológicos para hidrólisis y fermentación constituyen las principales áreas claves para destinar los esfuerzos de I&D.

Produktion fortschrittlicher Biokraftstoffe

Vier für die Zukunft vielversprechende Biokraftstoffe – Methanol, Ethanol, Wasserstoff und synthetischer Diesel – wurden systematisch auf ihr technisches und wirtschaftliches Potenzial hin untersucht sowie daraufhin, welch Verbesserungen zur Erfüllung dieses Potenzials notwendig wären. Schlüsseltechnologien zur Produktion dieser Kraftstoffe, wie beispielsweise Vergasung, Gasverarbeitung, Synthese, Hydrolyse und Fermentierung, und ihre Verbesserungsoptionen wurden studiert und modelliert. Die technologischen und wirtschaftlichen Leistungen der Produktionseinrichtungen wurden analysiert, wobei unterschiedliche Technologien und Maßstäbe berücksichtigt wurden. Die Produktionskosten für diese Kraftstoffe betragen heute 16 – 22 /GJHHV und werden in der Zukunft (2030) bei 9 – 13 /GJHHV liegen, vorausgesetzt, dass gewisse technologische Entwicklungen erfolgen und Biomasse zu einem Preis von 3 /GJHHV erhältlich ist. Mit 2 – 3 /GJfuel für jede /GJHHV Rohstoffveränderung haben die Ausgangsmaterialkosten einen starken Einfluss auf die resultierenden Biokraftstoffkosten. In Biomasse produzierenden Regionen wie Lateinamerika könnten die vier Kraftstoffe zu einem Preis von 7 – 11 /GJHHV hergestellt werden, was den Produktionskosten von Diesel und Benzin gleichkommen würde. Die Ungewissheitsspanne über die Biokraftstoff-Produktionskosten beträgt 15 – 30 %. Umfangreiche Vergasung, gründliche Gasreinigung und mikrobiologische Verfahren zur Hydrolyse und Fermentierung sind entscheidende Bereiche für weitere Forschungs- und Entwicklungsanstrengungen.

Introduction

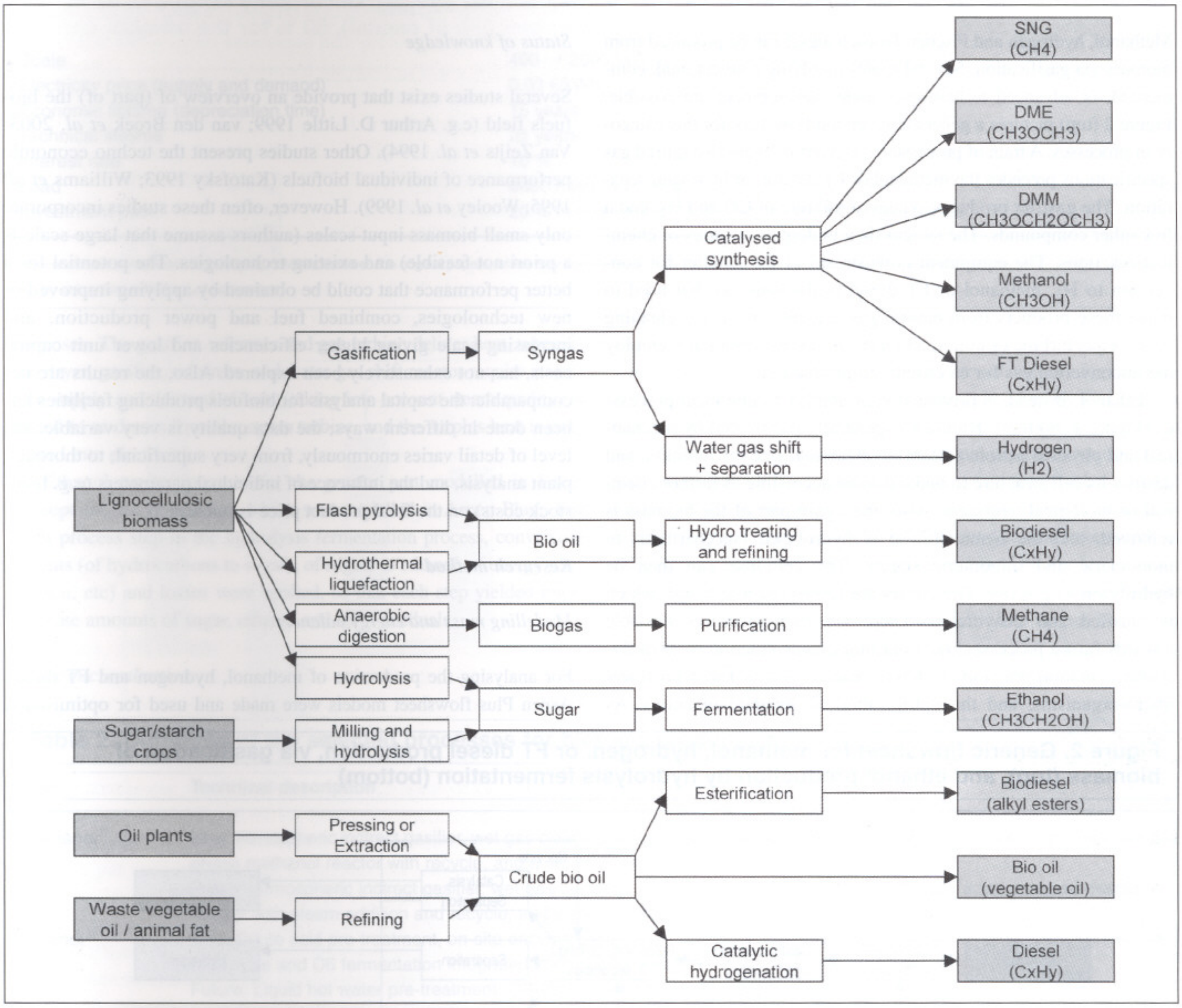
Biofuels are an important emerging business worldwide, driven by threatened fuel supplies, climate change concerns, the call for rural development, and ultimately by attractive policies. The amount of biomass feedstock that can be produced for fuels and other energy purposes is potentially very large (Hoogwijk *et al.* 2003).

A few main routes can be distinguished to produce biofuels: extraction of vegetable oils, fermentation of sugars to alcohol, gasification and chemical synthesis, etc to conceive methanol, ethanol, hydrogen, synthetic diesel, biodiesel, bio oil, etc (see Figure 1). All have very different properties and well-to-wheel performances.

Advanced fuels

Biofuels have often been classified in terms of "first" versus "second" generation. Generally, the first generation considered fuels produced from traditional agricultural (feed) crops by established tech-

Figure 1. Overview of conversion routes from crops to biofuels



nologies: biodiesel from oil crops and ethanol from sugar and starch crops. The second generation biofuels uses waste and whole crops as a feedstock and calls for new ("advanced") conversion technologies. Although these terms "first and second generation" can no longer be applied strictly, some biofuels derived from traditional agricultural crops have severe disadvantages related to the feedstock (Berndes *et al.* 2003; van den Broek 2000):

- Current high costs of rapeseed biodiesel and ethanol from cereals or beets
- Low net energy yield (100 – 200 GJ/ha/yr potentially achievable)
- Requirement of high quality (valuable) intensively managed agricultural land
- High fertilizer input
- Limited well-to-wheel reduction of fossil energy use and other environmental benefits.

The net energy yield of perennial crops (220 – 550 GJ/ha/yr), grasses (220 – 260) and sugarcane (400 – 500) is much higher. These crops can be grown on less valuable land (Rogner 2000). Use of lignocellulosic biomass (e.g. wood and grasses) is thus more favourable and gives better economic prospects to the future of biofuels. More types of feedstock are in principle suitable to produce a broader range of fuels than when applying traditional biofuels feedstock.

Higher overall energy conversion efficiencies and lower overall costs are the key criteria for selecting biofuels for the longer term. Key examples that are considered/developed that have good potentials are ethanol produced from lignocellulosic biomass, synthetic diesel via Fischer-Tropsch, methanol and hydrogen (Arthur D. Little 1999; Katofsky 1993; Turkenburg 2000; Williams *et al.* 1995). These four fuels are in attractive stages of research, development and demonstration. In this paper we present a detailed analysis of their long-term perspectives and RD&D needs. This gives insights both in the possible barriers to implementation that need to be overcome, and in the technological improvement options that should be stimulated. This paper is for a large part based on our earlier techno-economic studies on the production of methanol and hydrogen (Hamelinck and Faaij 2002), Fischer-Tropsch diesel (Hamelinck *et al.* 2004a; Tijmensen *et al.* 2002) and ethanol (Hamelinck *et al.* 2005), which have resulted in a PhD thesis (Hamelinck 2004).

Production of the selected biofuels

Methanol, hydrogen and Fischer-Tropsch diesel can be produced from biomass via gasification. Several routes involving conventional, commercial, or advanced technologies under development are possible. Figure 2 (top) 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 for electricity co-production.

Ethanol, instead, is produced via (largely) biochemical processes (Figure 2, bottom). Biomass is generally pre-treated by mechanical and physical actions (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. The sugars are fermented to ethanol, which is purified and dehydrated. There are two pathways possible towards future processes: the continuing consolidation of hydrolysis-fermentation reactions in fewer reactor vessels and with fewer micro-organisms, and the optimisation of separate reactions. As only the cellulose and hemicellulose can be used in the process, the lignin can be used for power production.

Status of knowledge

Several studies exist that provide an overview of (part of) the biofuels field (e.g. Arthur D. Little 1999; van den Broek *et al.* 2003; Van Zeijts *et al.* 1994). Other studies present the techno economic performance of individual biofuels (Katofsky 1993; Williams *et al.* 1995; Wooley *et al.* 1999). However, often these studies incorporate only small biomass input scales (authors assume that large scale is a priori not feasible) and existing technologies. The potential for a better performance that could be obtained by applying improved or new technologies, combined fuel and power production, and increasing scale giving higher efficiencies and lower unit capital costs, has not exhaustively been explored. Also, the results are not comparable: the capital analysis for biofuels producing facilities has been done in different ways; the data quality is very variable; the level of detail varies enormously, from very superficial, to thorough plant analysis, and the influence of individual parameters (e.g. feedstock costs) on the final product price is unclear.

Research method

Modelling mass and energy balances

For analysing the production of methanol, hydrogen and FT diesel, Aspen Plus flowsheet models were made and used for optimisation

Figure 2. Generic flowsheet for methanol, hydrogen, or FT diesel production, via gasification of biomass (top), and ethanol production by hydrolysis fermentation (bottom)

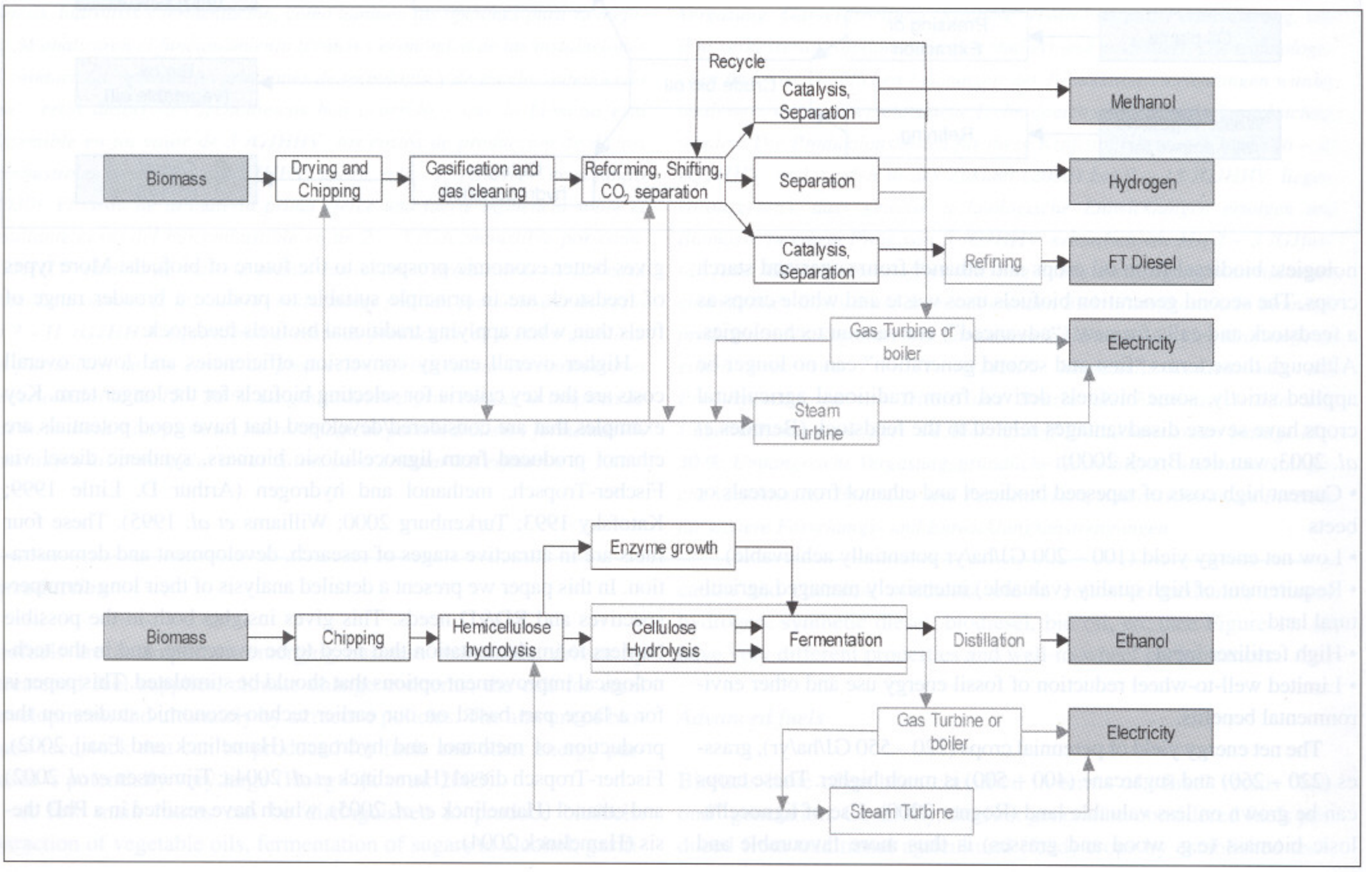


Table 1. Unified[1] set of input parameters

Scale	400 → 2000 MW_{HHV} input (short-term → long-term)
Electricity price (supply and demand)	0.03 €/kWh_e
Economic lifetime (depreciation time)	15 years
Technical lifetime	25 years
Interest rate	10 %
Load	8000 h (91 % of time)
Investment path	20 % in first year, 30 % in second and 50 % in last year

[1] Several input parameters were slightly different between the original papers, which may complicate direct comparison. Therefore, the results have been recalculated from the separate studies by using this unified set of parameters.

purposes. The gasifier, reformer and gas turbine deliver heat, whereas the dryer, gasifier, reformer, and water gas shift reactor require steam. The supply and demand of heat (taking into account steam quality) is added to or drawn from the steam turbine, and the surplus heat is converted into electricity.

Ethanol production was for the greater part modelled in Excel (except for the power isle, which was modelled in Aspen Plus). For each process step in the hydrolysis fermentation process, conversion extents (of hydrocarbons to sugars, of sugars to ethanol, of energy generation, etc) and losses were applied, so that each step yielded intermediate amounts of sugar, ethanol and solid residuals.

Economic evaluation

The resulting mass and energy balances served as basis for economic evaluation. Fuel production costs were calculated by dividing the total annual costs of a system by the annually produced amount of fuel. The total annual costs consist of annual capital costs, operating and maintenance (including maintenance, consumables, labour, waste handling), biomass feedstock costs and costs of electricity supply / demand (fixed power price). The total capital investment, or TCI, is calculated by *factored estimation*, based on known costs for major equipment as found in literature or estimated by experts, and translated to the actual equipment's size. Scaling-up has been done by using individual scale factors for each piece of equipment. The uncertainty range of such estimates is up to ± 30 %.

Table 2. Definition of the selected processes for biofuels production

Fuel	Technical description
Methanol[1]	Now: Atmospheric indirect gasifier, wet gas cleaning, steam reforming (partly fed by off gas), shift reactor, low pressure gas phase methanol reactor with recycle, and a steam turbine Future: Atmospheric indirect gasifier, wet gas cleaning, steam reforming (partly fed by off gas), a liquid phase methanol reactor with steam addition and recycle, and a steam turbine
Ethanol[2]	Now: Dilute acid pre-treatment, on-site enzyme production, enzymatic cellulose hydrolysis, SSF configuration (cellulose hydrolysis and C6 fermentation integrated in one reactor vessel), boiler and steam turbine Future: Liquid hot water pre-treatment, CBP configuration (enzyme production, enzymatic cellulose hydrolysis and co-fermentation in one reactor vessel), boiler and steam turbine
Hydrogen[3]	Now: Atmospheric indirect gasifier, wet gas cleaning, shift reactor, pressure swing adsorption for H^2 separation, and a combined cycle Future: Pressurised direct oxygen fired gasifier, hot gas cleaning, ceramic membrane with (internal) shift, and a combined cycle
FT diesel[4]	Now: Direct 25 bar oxygen fired gasifier, tar cracker, wet gas cleaning, no reforming, and once through FT synthesis at 60 bar with 90 % conversion Future: Direct 25 bar oxygen fired gasifier, tar cracker, wet gas cleaning, no reforming, and once through FT synthesis at 60 bar with 90 % conversion

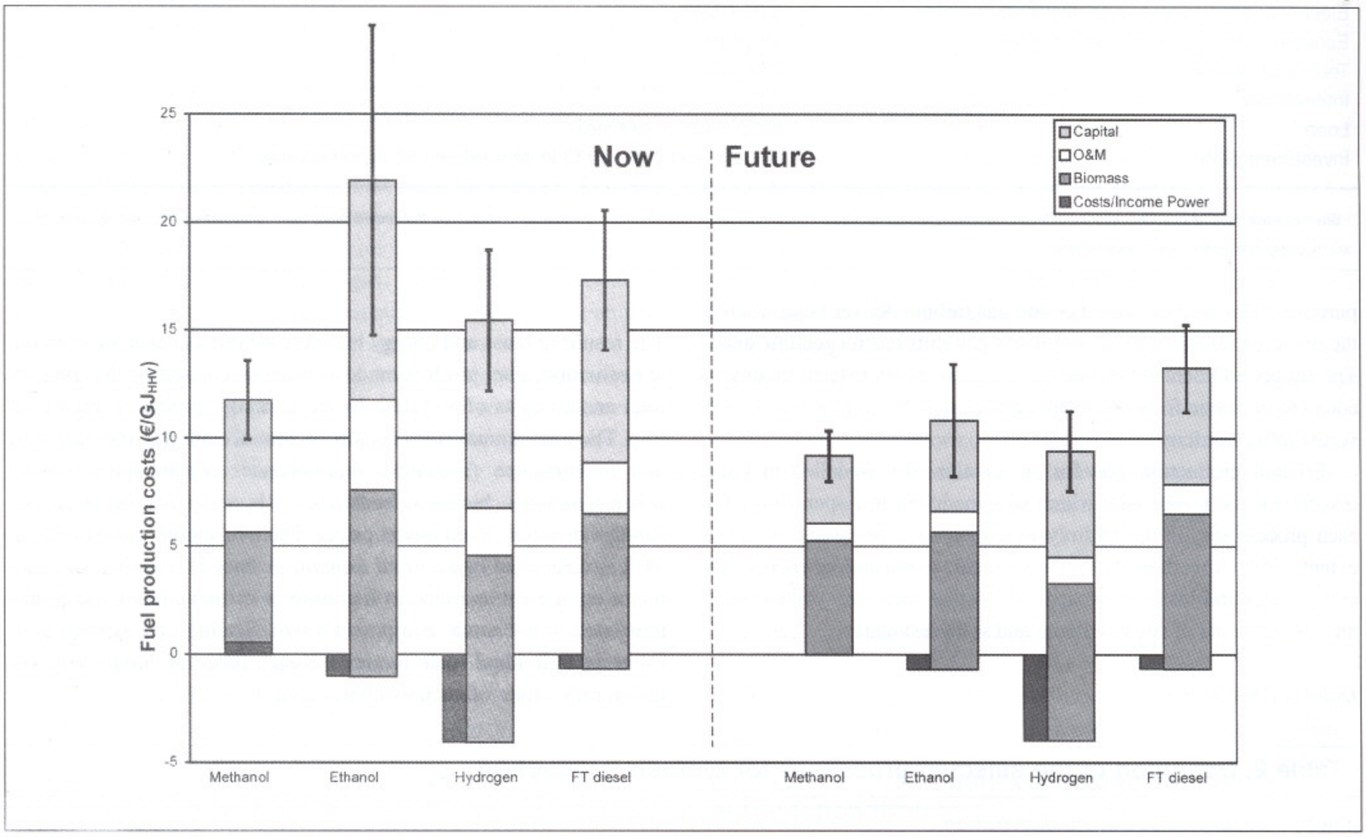
[1] Hamelinck and Faaij (Hamelinck and Faaij 2002) assessed six concepts for the production of methanol. Methanol now is the sixth of those concepts; it is the concept that performs best with currently available technology. Methanol future is the fourth and overall best of those concepts, but it applies a technology that is not yet available. The results quoted results are compensated for 15% cost reduction through learning, which was not incorporated in that study.

[2] Hamelinck *et al.* (Hamelinck *et al.* 2005) assessed three concepts for the production of ethanol via hydrolysis fermentation for short, medium, and long-term. Ethanol now is ethanol short-term concept, and ethanol future is the long-term concept of that study.

[3] Hamelinck and Faaij (Hamelinck and Faaij 2002) assessed five concepts for the production of hydrogen. Hydrogen now is the fifth of those concepts; it is the concept that performs best with currently available technology. Hydrogen future is the third and overall best of those concepts, but it applies technologies that are not yet available. The quoted results are compensated for 15 % cost reduction through learning, which was not incorporated in that study.

[4] Hamelinck *et al.* Iteratively assessed a broad range of concepts for the production of FT diesel (Hamelinck *et al.* 2004a). The FT diesel now concept is the concept that was found to perform best; it incorporates technology that is currently available. The future concept is the same concept with 15 % and 5 % cost reduction (learning + process improvement).

Figure 3. Breakdown of the production costs of selected biofuels (methanol, ethanol, hydrogen and FT diesel) now and in future. Feedstock costs 3 €/GJ$_{HHV}$. Time path also incorporates a scale increase: now 400 MW$_{HHV}$, medium-term: 1000 MW$_{HHV}$, and ultimate: 2000 MW$_{HHV}$. Uncertainty ranges of 30 % are applied to capital (and O&M, because this is a linear function of capital), 50 % for the ethanol concepts



For some of the process equipment costs are known from current practical reality, while other costs have been estimated from literature, or by consulted experts.

Although largely the same method was applied in the analysis of the selected fuels, there were some differences in the degree of detail, the amount of variations, and overall assumptions. The studies have been made comparable by applying a unified set of input parameters (Table 1).

Feedstock costs

The biomass feedstock costs are a major input parameter for the calculation of the biofuel production costs. Because of space limitations in this paper, we only mention that we assume that biomass could be delivered to Western Europe at about 3 €^{1}/GJ$^2_{HHV}$ (60 €/tonne$_{dry}$) in large amounts (170 – 290 EJ$_{HHV}$ annually) (Azar and Larson 2000; Hamelinck *et al.* 2004b; Hoogwijk *et al.* 2003; van den Broek 2000).

Selection for comparison

Based on the earlier broader evaluations, for each of the four fuels we present one concept for the short-term, and one concept for the long-term (see Table 2). For the short-term, we choose the best performing from concepts that are possible with currently available technology. For the long-term, we compare the ultimately best performing concepts, which may need further technological development.

Results and discussion

Technological insights

- Gasification based fuels

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 does not only introduce temperature and pressure leaps, but also 'material leaps' by reforming part of the product back to syngas. For methanol and hydrogen, however, 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 (Larson *et al.* 2001). 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 Fischer-Tropsch) are likely to have better economies of scale. The development of ceramic membrane technology is crucial to reach the projected hydrogen cost level. For Fischer-Tropsch diesel production, high CO conversion, either once through or after recycle of unconverted gas, and high C_{5+} 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, but this has not been researched in depth.

- Ethanol

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 400 MW_{HHV}. 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 come 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 need to be assessed more exact. Continuing development of new micro-organisms is required to ensure fermentation of xylose and arabinose. At the moment of writing (2006), a thirty-fold decrease of cellulase enzyme costs is already claimed to be achieved by Novozymes.

Economic performance

In the short-term ethanol and FT diesel facilities are the most expensive. These processes have a relatively low total (fuel + electricity) efficiency. In combination with high operating costs this makes cellulose ethanol the most expensive of these biofuels in the short-term.

A breakdown of the production costs into capital, O&M, feedstock and power costs is shown in Figure 3. A 30 % uncertainty should be applied to the total capital investment of methanol, hydrogen, and FT diesel concepts. The capital costs for the ethanol concepts are estimated to have a higher uncertainty (50 %), because of the less detailed analysis. The uncertainty bars in Figure 3 show that the eventual influence of these uncertainties to the production costs is could be up to 30 % to 50 %.

The bare influence of scale on the biofuel production costs is made visible in Figure 4. Analysis of the curves yields different overall scale factors for the production facilities' total capital investments for the different technologies. Also, these scale factors change over the whole 80 – 2000 MW_{HHV} range. All thermal gasification based processes experience a stronger influence of scale between 80 and 400 MW_{HHV}, than ethanol production. This is because hydrolysis fermentation takes place in vessels that have a small maximum size.

In the base situation (Figure 3) feedstock (at 3 €/G_{HHV}) accounts for 45 – 58 % of the total product costs. The influence of biomass feedstock price depends on the conversion efficiency from feedstock to fuel, e.g. a η_{HHV}, fuel of 35% (ethanol-now) implies that with every € feedstock cost reduction, the production costs reduce with 2.9 € (1/0.35). A much more efficient process, such as "methanol now" thus becomes relatively more attractive at high feedstock costs (refer to Figure 5). Since cheap feedstock will be used first (up to 3 €/GJ at gate), process improvements may initially focus on capital, O&M an power cost reduction.

The fuels could also be produced in the biomass supplying countries, provided that the amount of cheaply available biomass locally suffices, after which the biofuel is internationally shipped. This has two advantages: the elimination of the costly densification step (pellets) otherwise necessary to minimise long distance transport costs, and the higher energy density of the transported commodity. The joint cost reduction is about 9% for methanol (Hamelinck *et al.* 2004b). Although ethanol has a higher energy density than methanol, the cost advantage will be practically the same. It can be concluded that this route is very attractive for sugarcane ethanol from Brazil.

Broader comparison

The current prices for sugarcane ethanol in South East Brazil are in the lower range of the costs achievable for the advanced biofuels discussed, 7 – 9 €/GJ_{HHV} (Goldemberg *et al.* 2004). International alcohol shipment from Latin America to Europe will not add more than 0.5 €/GJ. If road tanker transport from a inland production location to the harbour were necessary, this would add half a euro extra per GJ per 100 km (Hamelinck *et al.* 2004b).

Delivered costs for other fuels are reported to amount 21 – 38 €/GJ_{HHV} for ethanol from wheat, 15 – 29 €/GJ_{HHV} for RME, sugar beet ethanol 26 – 40 €/GJ_{HHV}, and higher when the production of feedstock receives no subsidy. Dimethylether (DME) is projected to cost about 13 €/GJ_{HHV} (DME), and substitute natural gas (SNG) 13 €/GJ_{HHV} (Arthur D. Little 1999; van den Broek *et al.* 2003; Van Zeijts *et al.* 1994).

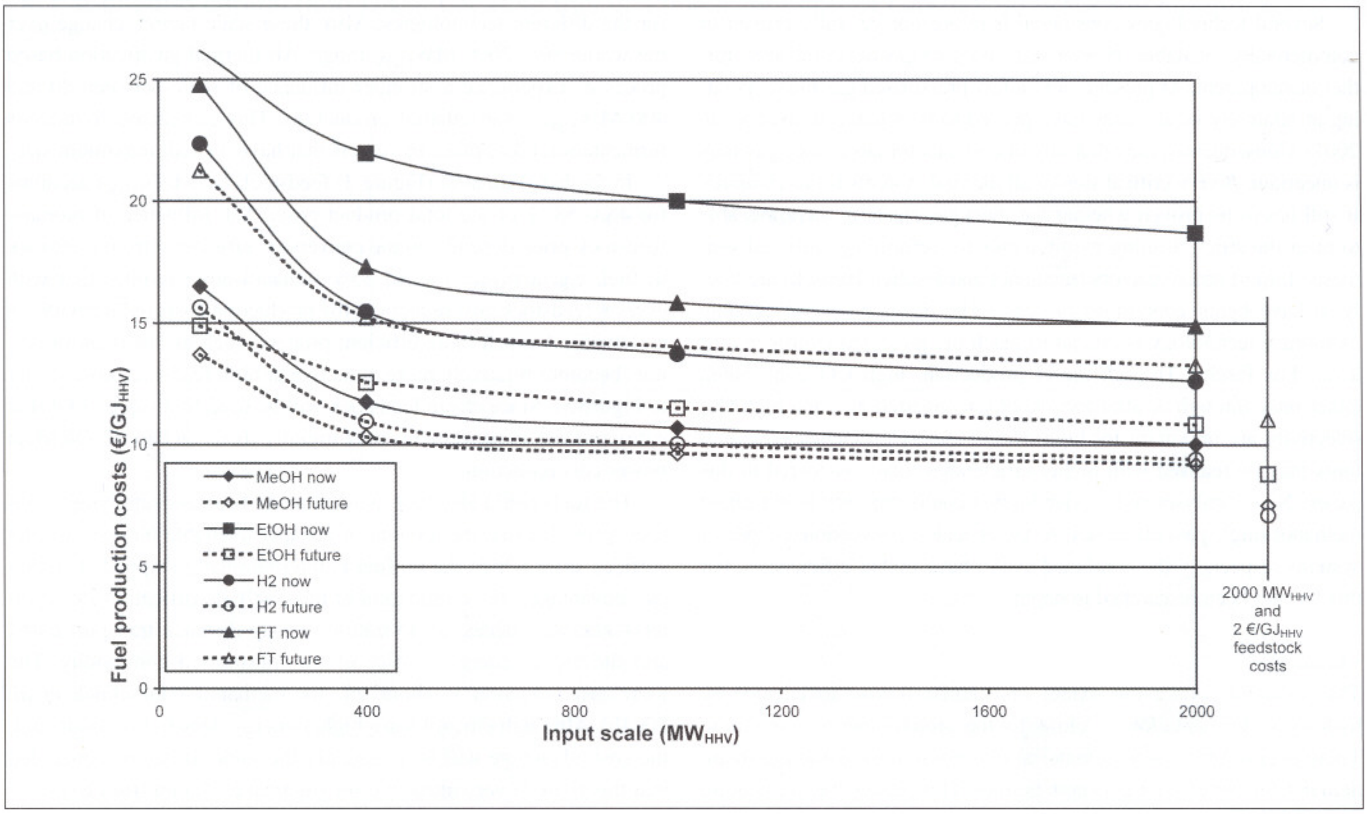
Conclusion

Main conclusions

Through expected process improvements, technological learning and scale enlargement, production costs can decrease and/or efficiencies can go up. Technological learning can take place through increasing production capacity and experience.

The production of four promising biofuels – methanol, ethanol, hydrogen, and synthetic diesel – was systematically analysed, based on detailed pre-engineering analyses. Production costs of these fuels range 16 – 22 €/GJ_{HHV} now, down to 9 – 13 €/GJ_{HHV} in future (2030). This

Figure 4. Influence of input scale on the production costs of selected biofuels. Feedstock costs 3 €/GJ_{HHV}, with a sensibility towards 2 €/GJ_{HHV} at 2000 MW_{HHV} input



performance assumes both certain technological developments as well as the availability of biomass at 3 €/GJ_{HHV}. The feedstock costs strongly influence the resulting biofuel costs by 2 – 3 €/GJfuel for each €/GJ_{HHV} feedstock difference. In biomass producing regions such as Latin America, the four fuels could be produced against 7 – 11 €/GJ_{HHV}. These costs should be compared to the rising gasoline and diesel costs of 10 €$_{2005}$/GJ at the end of 2004 and 12 €$_{2006}$/GJ[3] at the time of writing. The uncertainties in the biofuels production costs are small when considering the large uncertainty in future (2030) gasoline and diesel prices.

The key fuel chains for the short-term seem to be methanol and FT diesel, while ethanol from lingo-cellulose emerges in the medium-term. Ultimately, hydrogen may offer the best perspective; but requires breakthroughs in hydrogen storage technology to tick the balance.

RD&D issues

The gasification-derived fuels require the development of large (about 400 MW_{HHV} input) pressurised gasifiers, a gas cleaning section that matches the catalyst's specification, increased catalyst selectivity (for FT diesel production), and ceramic membranes in the case of hydrogen. Hot gas cleaning and CO_2 removal positively affect the total plant efficiency, but the economic effect is ambivalent. Co-producing electricity and biofuels deserves further research. Synergy with fossil fuels (co-feeding) could facilitate both scale enlargement and cost reduction. More research is desired in this field.

The production of ethanol from lignocellulose biomass requires the development of more efficient pre-treatment technology, and of micro-organisms that yield higher conversions, as well as the integration of several conversions into fewer reactors.

This paper is based on the PhD thesis "Outlook for advanced biofuels" by Hamelinck.

Endnotes

[1] All costs in this paper are in €$_{2003}$, unless indicated otherwise, inflation 2.5 % annually, 1 €$_{2003}$ = 1 US$_{2003}$.

[2] Energy is preferably expressed on Higher Heating Value basis, indicated by the subscript HHV. LHV indicates Lower Heating Value, if no subscript is given, the definition is unknown.

[3] At crude prices of about 65 US$/bbl, according to the US Energy Information Administration.

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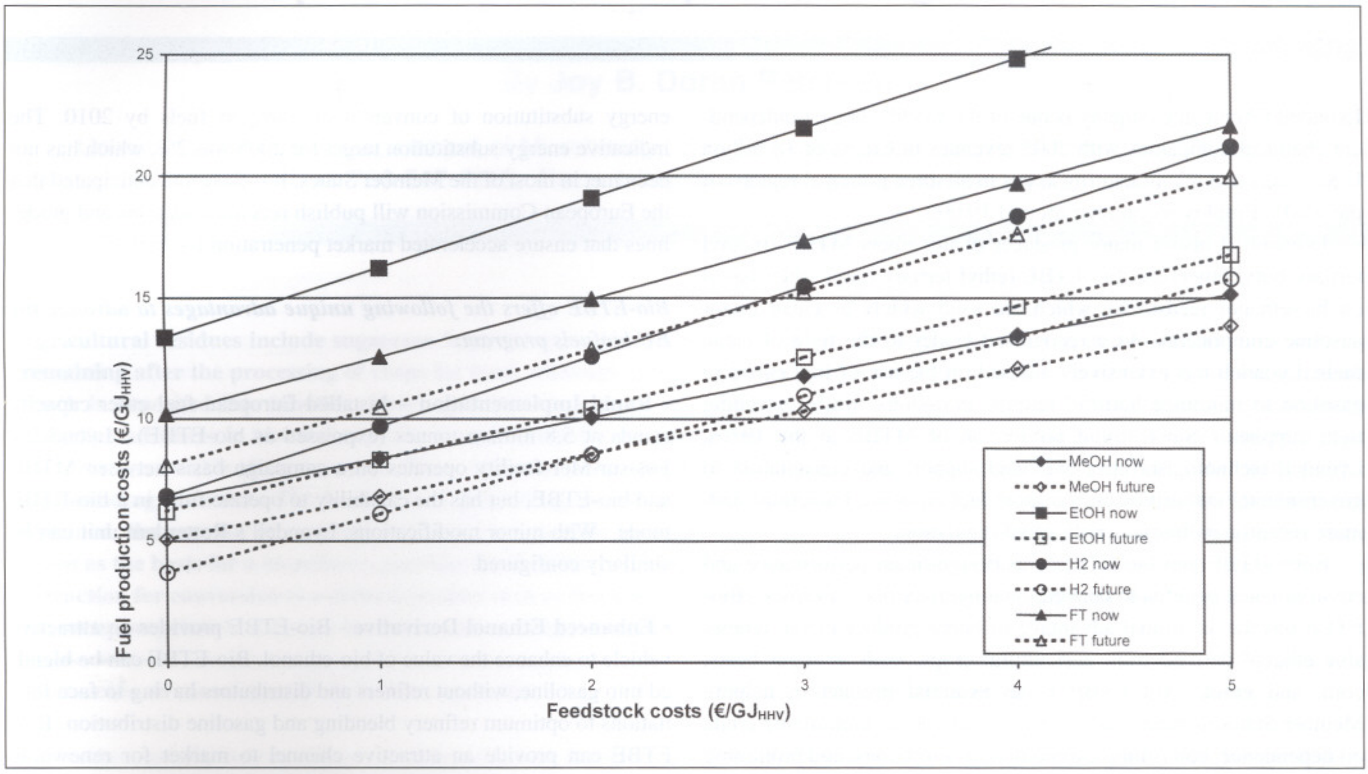
Figure 5. Influence of feedstock costs on the production costs of selected biofuels (400 MW_{HHV} input)



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