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Sustainable transportation biofuels today and in the future – Summary

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Pål Börjesson, Lund University
Joakim Lundgren, Luleå University of Technology (Bio4Energy)
Serina Ahlgren, Swedish University of Agricultural Sciences
Ingrid Nyström, f3 and CIT Industriell Energi

THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

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CONTENT

Knowledge overview

This report provides an overview of current knowledge concerning potential use and sustainability of biomass and production of sustainable biofuel from raw material to finished fuel (i.e. well-to-tank, or WTT). The report is based on the background report that f3 submitted to the Fossilfrihet på väg (literally Fossil-Free on its way) study from 2013, but has been updated with new data, as necessary and in accordance with access to new research findings. Based on systems analysis, WTT performance for various alternative production chains are presented, in respect of:

- Total energy efficiency
- Greenhouse gas performance
- Land efficiency
- Economy

The report only covers biofuels and does not include other process chains for production of renewable fuel. Particular focus is placed on biofuel systems that are, and may be, relevant for production located in Sweden as well as those systems that contribute most to today's renewable fuel and/or have the greatest long-term potential for sustainable production in larger quantities.

For complete supporting documentation, including method descriptions, all detailed calculation data and all references, see Börjesson et al, 'Dagens och framtidens hållbara biodrivmedel (Sustainable transportation biofuels today and in the future)', f3 2013:13, 2013 (in Swedish). In this summary, facts and data have been updated to the extent deemed relevant. Reference is specifically made where this occurs. The summary has been made by the original authors, with the support of additional reviewers within f3 – Swedish Knowledge Centre for Renewable Transportation Fuels. For further information about f3's activities, see www.f3centre.se.

This report is a translation of "Dagens och framtidens hållbara drivmedel – i sammandrag", Rapport f3 2016:03.

Summary

Important issues for biofuels today and in the future comprise sustainability aspects, the potential of biomass for energy purposes, and the performance of different production chains from raw material to finished product. In general, sustainability cannot be determined based on type of transportation fuel, but each production system must be judged separately. In addition, its performance depends on local conditions, production volume and time perspective.

Consistent application of well-formulated sustainability criteria are necessary for continued development of transportation biofuels. Such criteria should include several aspects, for example effects on biodiversity, land use and socioeconomics, in addition to greenhouse gas (GHG) performance. With well-configured sustainability criteria, use of biomass for production of transportation fuel is sustainable and reduces GHG emissions.

Increasing production and use of sustainable biofuels on a large scale at a sufficiently fast pace requires policies that promote the development of the most environmentally-effective systems, have sufficient flexibility to include new technological developments and are internationally supported.

The sustainability can be improved through, for example, more efficient processes, better utilisation of by-products, modified energy use, etc. Further, measures can be taken to reduce competition for land use and potential negative indirect land use effects (i.e. when global land use is affected).

In Sweden, the prospects for increasing production of sustainable fuel based on raw material from both agriculture and forestry are good. Under current conditions, the annual biomass production could increase by 40-50 TWh, which is equivalent to about 22-32 TWh of transportation biofuel (in addition to electricity, heating and other by-products). In turn, this corresponds to roughly one third of today's use of petrol and diesel for road transport. In the longer term, the potential for biofuel production in Sweden is even larger.

The majority of existing and future biofuel chains display high energy efficiency, good GHG performance and reasonable production costs. For lignocellulose-based transportation fuel and biogas from organic waste, external energy input per unit biofuel produced is below, or at approximately the same level as, that of petrol and diesel (as well as for sugar cane ethanol from Brazil). A higher energy input is required for biodiesel from rapeseed and wheat-based ethanol. However, the performance for both of these biofuels is substantially improved when indirect benefits of by-products and process development are included in the analysis. The reduction in GHG for all biofuels included is over 50%, compared with today's fossil-based transportation fuels. In these calculations, it is important to include all products from the production plants in the analysis, something that is not fully implemented in the methodology that is currently used for the EU's regulation system.

The production cost is estimated to be below that for fossil fuels (including CO_2 tax) for future forest-based synthetic natural gas, sugar cane ethanol and biogas, while for other biofuel chains it is at roughly the same level or somewhat higher. However, the comparison is highly uncertain and depends, as stated, on the entire biofuel chain.

Increasing production and use of sustainable biofuels on a large scale at a sufficiently fast pace requires policies that promote the development of the most environmentally-effective systems, have sufficient flexibility to include new technological developments and are internationally supported. A very high level of complexity sets high demands on methodology, research-based data and on the knowledge level of decision makers.

Chapter 1

Production of biofuels for transportation

Biofuels for transportation can be produced through a large range of production chains (see Figure 1), depending on raw material used, conversion process and biofuel produced. The vast majority of biofuels, as for example ethanol, can be produced by several different production chains. Further, the production process does not itself determine the performance of the chain, as the performance also to a high degree depends on raw material, geographic location, transport distance and possibilities for integration with other plants. In other words, efficiency or environmental impact cannot be assessed solely on the basis of which fuel is intended, but must rather be evaluated based on each production chain as a whole.

The potential for production of biofuel via a particular production chain is limited. Some production chains are based on raw materials with large potential and/or high raw material flexibility, while others are entirely dependent on a specific crop or residual product. A production chain with high efficiency, low environmental impact and good economy will thus not necessarily have a major impact on the total transportation fuel market, if the potential is limited. Two important driving forces for the development of new production chains are the possibility of increasing the raw material base (e.g. use of forest raw materials or algae) and producing fuel of a specific quality (e.g. synthetic diesel or aviation fuel).

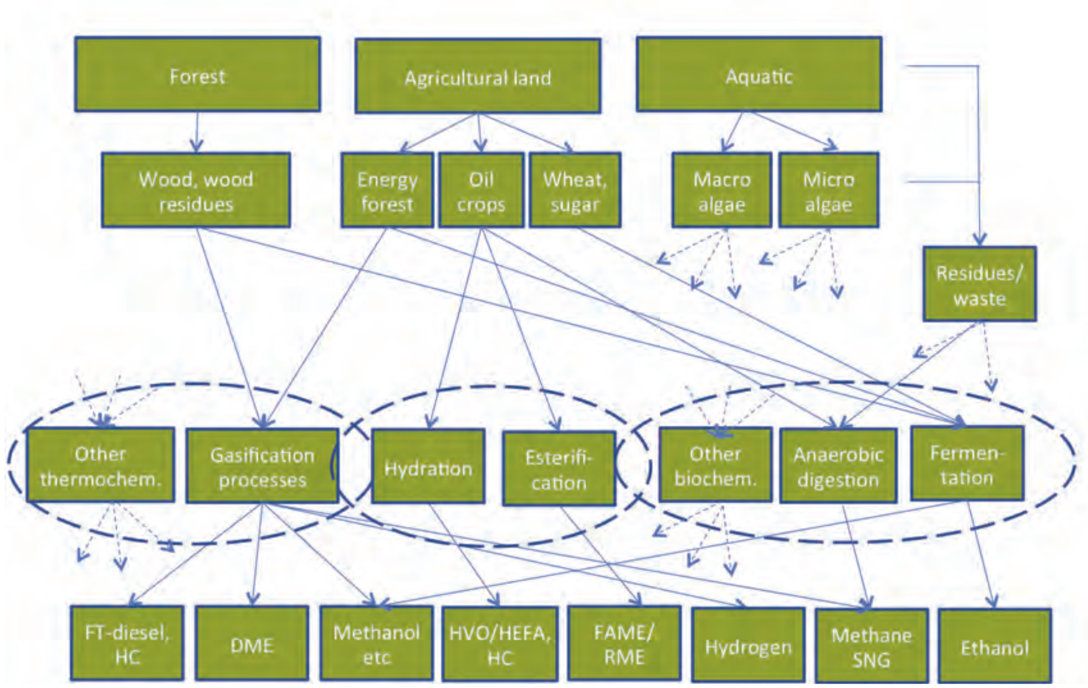

Figure 1. *Illustration of the most relevant production chains for biofuel production. Overall, there are a large number of possible alternatives and developments are also continuously being made, why the illustration cannot claim to be complete. Raw materials based on different types of residual products and waste can be relevant in all chains.*

DME *= Dimethylether* ***FT*** *= Fischer-Tropsch* ***FAME*** *= Fatty Acid Methyl Ester* ***HC*** *= Hydrocarbons* ***HVO*** *= Hydrogenated Vegetable Oil*
HEFA *= Hydroprocessed Esters and Fatty Acids (= HVO)* ***RME*** *= Rapeseed Methyl Ester* ***SNG*** *= Synthetic Natural Gas*

Different production chains for biofuel can be classified based on the raw material's chemical properties, as these to a large extent govern which production processes are relevant. This enables definition of three primary groups[1]:

- Sugar or starch-based raw materials, i.e. for instance sugar cane, sugar beet, wheat, maize and other cereals.
- Oil-based raw materials, i.e. rapeseed, oil palm and other oil-yielding plants, but also residual products from the forest industry, such as tall oil, and animal fats from offal.
- Lignocellulose, i.e. primarily different types of forest raw materials, but also residual products from agriculture such as straw and bagasse.

The production chains can also be categorised according to type of production process. A broad breakdown, which includes most of the process chains which have currently come furthest in their development, can for example be made in three different process platforms; thermochemical, biochemical and oleochemical conversion[2].

Finally, it is of course possible to divide the chains based on type of biofuel that is produced. However, as indicated above, performance can differ greatly, depending on other conditions, so that the difference between 'good' and 'bad' production chains for the same fuel is then larger than the differences between different fuels[3].

Thermochemical conversion
The process platform includes gasification and other thermochemical conversion such as pyrolysis. There are several different gasification technologies, and basically all types of fuel can be produced via gasification, though with different total efficiency. Gasification, as well as pyrolysis, is primarily relevant for lignocellulose-based raw materials, which are difficult to convert in other ways.

Biochemical conversion
Biochemical conversion includes fermentation, anaerobic digestion and other variants of enzymatic and bacterial conversion. Fermentation mainly converts sugar and starch-based raw materials to alcohols (primarily ethanol). However, lignocellulosic material can also be converted, through pretreatment and use of other yeasts/enzymes. Anaerobic digestion entails bacteria conversion of biomass to biogas, which mainly consists of methane and carbon dioxide. After purification (from CO_2 and other contaminants), biomethane is obtained.

Oleochemical conversion
Oleochemical conversion comprises hydrogenation and esterification of oil-based raw materials (or residual products), which can also be described as catalytic, thermochemical processes. The hydrogenation process reduces the oxygen and sulphur content in the raw materials to a mixture of paraffin hydrocarbon, such as renewable diesel for example. The esterification process replaces the glycerol element in the raw material with an alcohol, usually methanol, and forms esters (FAME, fatty acid methyl ester), for example RME (rapeseed methyl ester). In addition, catalytic decomposition of lignin, for further refinement to paraffinic hydrocarbons, is currently under development[4].

1. *These groups thus include raw materials that are dependent on integration with other industrial production, for example, black liquor and tall oil from the forest industry, and waste, which has a more mixed composition. In a longer time perspective, algae are being discussed as a possible raw material with large potential. Algae have different properties, depending on type of algae, and can therefore be located in several of these groups*
2. *However, the categorisation of a process is not always obvious and in some cases there is a certain amount of overlap between the groups.*
3. *Whether alternative biofuel production is specified according to raw materials, process or fuel, it has been common to use the terms first, second and third generation. These terms are difficult to define and are in many cases misleading. We have therefore consistently chosen to avoid this division altogether and instead discuss performance linked to individual production chains.*
4. *However, no published system studies have been performed for this development path and neither is there currently sufficient data available for such an analysis. This report consequently does not include WTT performance for this type of process chain.*

Chapter 2

Biomass as a sustainable resource

Sustainability is defined in the 1987 Brundtland report as: ”Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Sustainability is usually discussed on the basis of three pillars: ecological, economic and social sustainability.

Here the main focus is on aspects that affect the ecological, and to some extent social sustainability, of biomass use. These aspects are actually similar regardless of final biomass use – for food, material or bioenergy in general. However, the most discussed and studied questions by far have concerned the use of biomass for production of transportation fuel.

2.1 GHG EMISSIONS LINKED TO BIOFUEL CHAINS

GHG emissions from biofuels can be linked to the entire chain: both emissions from bioenergy use as such; and emissions from various process steps, including cultivation, transportation and industrial production process for the fuel (see Figure 2). The debate about whether bioenergy use as such is carbon dioxide neutral or not, relates to if carbon dioxide released during biomass combustion can be considered to be absorbed by new biomass. In such a case, net emissions of carbon dioxide are zero. In principle, this question only concerns wood fuel from stemwood, which has a longer rotation period (time between absorption and emission) for carbon dioxide than agricultural products.

For extraction of forest residues (branches, tops and stumps) after final logging, the interesting question concerns instead the difference between leaving the residues in the forest and removing them. Since residues that remain in the forest would have a slight contribution to the long-term soil carbon stocks, it is demonstrated that there is a minor impact on the climate from using the residues for bioenergy instead. In a 100 year perspective, the use of branches and tops leads to a lower climate impact than the use of stumps. This conclusion also applies in a 20 year perspective, but with a smaller difference between the types of feedstock. In all cases, however, the use of forest residues has a considerably lower climate impact than use of fossil carbon[5].

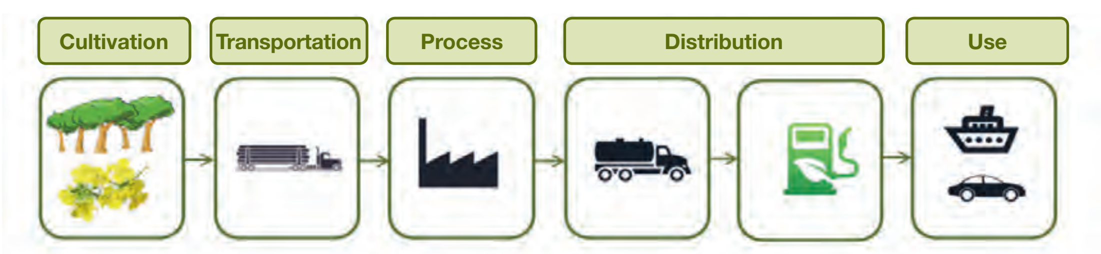

Figure 2. *Illustration of the different stages of the process chain, which all can entail GHG emissions.*

5. Zetterberg & Chen (2011).

The climate benefit of wood fuel from stemwood can be summarised as follows[6]:

- From a long-term perspective (which is relevant when evaluating long-term climate changes), which considers extraction of forest biomass at a property and landscape level, bioenergy is an effective alternative from a GHG point of view. Even if the slight reduction of long-term soil carbon stocks from increased forest residue extraction are accounted for, in the long run bioenergy will clearly be a better alternative than fossil fuels.
- However, studies which evaluate individual bioenergy projects at stand level with a short-term time perspective usually demonstrate a relatively poor GHG performance for biomass.
- Bioenergy should therefore be evaluated from several perspectives, so that a balanced picture can be achieved. Moreover, an emissions space can be 'saved' from an initial development phase for bioenergy systems which in the long term delivers major reductions in GHG.

GHG emissions during the *cultivation stage*, are an important factor primarily for agriculture-based biofuel. Cultivation requires a large number of inputs, e.g. machinery, diesel, oil, fertilisers, pesticides, and the production of these inputs gives rise to emissions. In particular, the production of nitrogenous fertiliser affects the total emissions, as it is based on fossil energy and also that nitrous oxide, which is a very powerful GHG, is formed and released in the process.

GHGs are also emitted on farms, e.g. with use of diesel and oil for tractors, and use of nitrogen for fertilisation, as microbial conversion of nitrogen in the fields leads to nitrous oxide formation. This applies for both mineral nitrogen and organic nitrogen, such as farmyard manure, as well as for plant residues left in the fields. Emissions of nitrous oxide in cultivation often constitute a large part of total GHG emissions of a crop, as well as a major source of uncertainty in the GHG performance of biofuels. In addition, the harvest level naturally has a major effect on the results. High yield crops are in general connected with lower emissions per unit produced.

Transportation of raw materials and fuel often accounts for a small proportion of the environmental impact. Energy and other inputs, e.g. chemicals, which are used in *the production process* can however be of crucial significance. Energy and material use, and thereto related GHG emissions, vary to a high degree between different types of production processes

2.2 PLANT NUTRIENT BALANCE

Increased extraction of biomass for biofuel production can affect the soil's plant nutrient balance. Some transportation biofuel systems enable recirculation of nutrients that have been removed, e.g. methane is extracted in a biogas process, but all nutrients remain in the digestate which is subsequently restored to farmland. For ethanol based on crops, all nutrients are to be found in the draff, which is often used as animal feed, subsequently ending up in manure that can be restored to the fields. In other processes, such as combustion and gasification, all nitrogen dissipates into the atmosphere, however, potassium and phosphorus remain in the ash and can be restored to the soil.

2.3 LAND USE CHANGE

The impact of biofuel production can also comprise changed use of land; both directly as (dLUC, indirect land use change) and indirectly (iLUC, indirect land use change). In short, dLUC is linked

6. *Berndes m fl (2012).*

to the field where the raw material for the biofuel is cultivated, while iLUC occurs elsewhere, as increased demand for biofuel leads to a redistribution of land use.

The reasoning behind iLUC is highly theoretical and the argument for iLUC is only relevant when the effect of individual sectors or products such as transportation biofuel is studied[7]. We can observe changed use of land around the world, in the worst case, for example, new cultivation in what was previously forest or valuable grassland. On the other hand, if we look at the planet as a whole, we cannot divide changed use of land into dLUC and iLUC. Neither is it possible to link change in land use in, for example, South America to an individual farmer's activity in, for example, Southern Sweden.

In other words, iLUC concerns market effects. Trying to establish what is actually happening in different markets when biofuel production on a large scale is initiated and how this affects land use in all countries is tremendously complex. One of the predominant methods for establishing iLUC is to use economic equilibrium models. The results from different studies vary greatly, and there are numerous and major sources of uncertainty, e.g. the economic models are not able to distinguish between direct and indirect land use changes. Other factors which make the results very difficult to compare are, for example, that the models have different approaches, different assumptions about the oil price, land price, trade policy etc. as well as different handling of spatial resolution, land types, deforestation, soil carbon changes, inclusion of nitrous oxide, and time perspective.

The theory about indirect effects is naturally also applicable to fuel based on lignocellulose raw materials from agriculture and forestry as well as for fossil fuels. However, most studies that have been conducted on iLUC concern crop-based fuels.

Indirect land use change (iLUC) and associated negative and positive sustainability effects are important to consider when discussing political initiatives in relation to biofuels. Besides large uncertainties on the size of iLUC effects, it raises, however, also the question whether it is in principal possible to legislate to avoid indirect effects, via, for example, the introduction of iLUC factors. Other alternatives are to implement international agreements that regulate all land use or to introduce a global tax on carbon dioxide emissions which also includes soil emissions. Individual countries can also act through only buying biofuel from countries that report LUC emissions and have a responsible forest policy.[8]

2.4 SUSTAINABILITY CRITERIA

There are a number of national and international regulations to ensure the sustainability of biofuel. For example, the EU has introduced the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD) and in the USA there is the Renewable Fuel Standard. There are also many different voluntary certification systems, for example 'Round Table of Sustainable Fuels'. In general, GHG emissions, biological diversity and socioeconomic aspects are dealt with in many of the systems, while indirect use of land and social sustainability criteria are not usually included. There is, however, an ISO standard (International Standardisation Organisation) with a framework for evaluating broader sustainability aspects of bioenergy, where environmental, social and economic aspects are included (ISO 13065:2015 Sustainability criteria for bioenergy). For example, the impact of factors as divergent as GHGs, biodiversity, energy efficiency, water use, human rights and economic sustainability are

7. Samma argument gäller också för ökad efterfrågan på t ex mat, men forskning kring iLUC har hittills bara fokuserat på biodrivmedel. När mark byter användning fås också en rad effekter, såväl sociala, ekonomiska som miljömässiga. Debatten, politiken och de vetenskapliga studier som publiceras inom ämnet har dock ett starkt fokus på växthusgaser.

8. Ahlgren & Börjesson (2011).

included. There are well developed indicators for some of these categories, while the standard is less detailed for others.

Sustainability criteria within the EU

The EU's Renewable Energy Directive (RED) contains requirements that transportation biofuel must reduce GHG emissions by a given percentage, compared to a fossil reference, to be approved as sustainable. For older biofuel plants, the reduction currently has to be a minimum of 35%, however, the requirements are set to increase by 2018, at which time the reduction must be at least 50%. The requirements are more stringent for new plants (in operation after October 2015), the reduction for them must be a minimum of 60%.

There are also other sustainability requirements in the directive. Raw materials for production of biofuel may not origin from virgin forest, protected nature areas or grasslands with a high level of biodiversity. Land with a high carbon content (such as wetlands or peat bogs) can only be used provided that the land use has not changed since 2008..

The directive gives specific instructions for calculation of GHG emissions. Under certain conditions, the normal values given in the directive can be used, in other cases the actual values must be calculated, or a combination of the two must be applied.

The distribution of total emissions between products, with simultaneous production of more than one product (so-called allocation), is based, according to RED, on the products' lower thermal value. However, no up-stream GHG emissions are allocated to raw materials classified as waste and crop residues, such as straw, bagasse and husks (i.e. only emissions arising from transports and conversion into biofuels are included). Carbon dioxide from bio-based products (in the combustion stage) is set at zero and is thus not regarded as having any climate impact.

Between 2012 and 2015, discussions were held on revision of the RED. These resulted, in autumn 2015, in a specific directive with regulations regarding indirect land use. The gist of this was that the target of 10% renewables in the transport sector must be met by a maximum of 7% biofuel from food crops, that biofuels from certain raw materials are classified as advanced biofuel and can be double counted in meeting the targets, and that iLUC emissions must be reported (based on iLUC factors in a specific list), but that these emissions are not included for fulfilment of the emission reduction criteria above.[9]

Several of the voluntary certification systems are linked to RED, which means that a company can utilize an EU approved certification system to prove that it meets the sustainability requirements that are required in the directive.

2.5 PROACTIVE MEASURES FOR INCREASED SUSTAINABILITY

Transportation biofuels' sustainability performance can be improved through proactive measures, such as more efficient processes, better utilisation of by-products, changed energy use and so forth. It can also be improved through measures to reduce the competition for land and potential iLUC effects. The potential is not solely dependent on developments within the energy and transportation fuel sectors, but also on population growth, diet, production increases within agriculture and forestry, the proportion of protected nature areas and development of policy within agriculture and forestry[10].

9. The European Parliament and Council Directive (EU) 2015/1513, 9 September 2015, published in 'EU Official Journal (L 239)'. The information in this section has been updated compared with the main report.

10. Smith et al (2010).

Some measures, which can contribute to increasing use of bioenergy, without increasing the competition for land are:

- Use of waste, residual products or other raw materials that do not require high land-use (e.g. algae).
- Increase biomass production on land that is already cultivated, through new plant varieties, chemical pesticides, fertiliser, mechanisation, irrigation etc.
- Use unexploited land, such as abandoned agricultural land and marginal land, as well as fallow land.
- Reduce the proportion of biomass produced that is rejected, impaired or attacked by vermin. Today about one third of all food produced is discarded.[12]
- Change diet and reduce meat consumption, which would make almost one fifth of global agricultural land available for other purposes.

A general conclusion in the literature is that the production of bioenergy and biofuel can be increased, while simultaneously minimising the effects on agriculture markets and food production. We currently use a very small proportion of the cultivated land for transportation biofuel (see Figure 3). However, the share of biofuel in the transport sector (globally) is also only 3%. An increasing population naturally increases the risk of land becoming scarce, which could lead to greater competition and environmental impact.

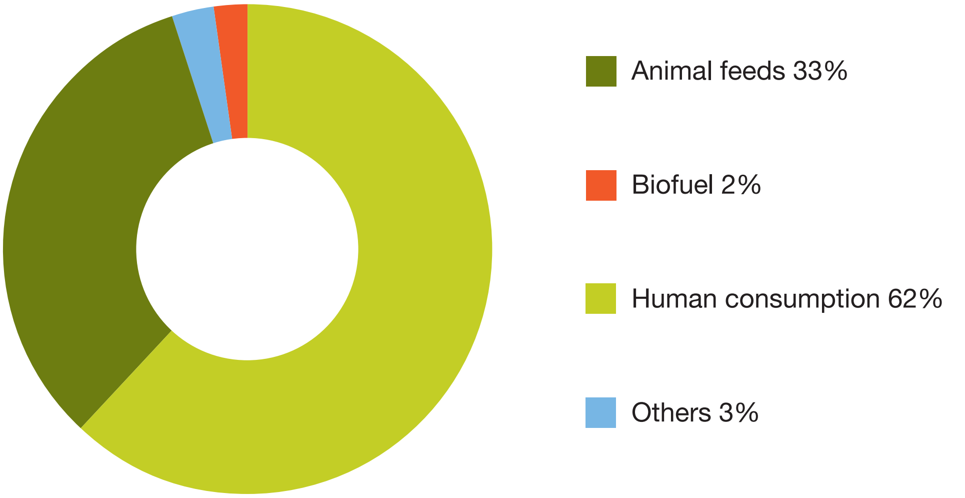

Figure 3. *Global distribution of arable land (i.e. not including permanent grasslands for pasture (from the compendium in Hallström et al, 2011).*

11. For example, the Swedish Board of Agriculture estimates that there are 100,000 hectares of abandoned (previously cultivated) agricultural land in Sweden, and according to Eurostat, the total amount of fallow land within the EU was 8.7 million hectares in 2009 (SJV, 2009; Eurostat, 2013).

12. According to FAO (2006), according to Foley et al (2011) it is approximately half.13. GEA (2012); IEA (2011).

Chapter 3

Biomass with significant potential

The IPCC has made a compilation of studies that try to estimate the global potential for bioenergy[14]:

- The estimates of the technical potential for bioenergy from agriculture, forestry and waste vary in the studies between 50 and 1,000 EJ/year.
- Including ecological and economic restrictions, biomass is deemed to be able to contribute between 120 and 155 EJ/year (primary energy) to the energy system by 2050.
- As a comparison, the world's total energy use is currently equivalent to about 475 EJ/year (130 billion TWh) and the amount of energy that is harvested as food, fodder and fibres is 219 EJ/year.

Another study draws the conclusion that if 50% of the economic bioenergy potential was to be used for transportation biofuel, it could cover 25-30% of the global transportation fuel demand[15].

These potentials do not include biomass from algae. Cultivation of algae is motivated by the prospect of achieving high productivity per land area and that non-productive land and water resources of low quality (e.g. contaminated water or salt water) can be used. Global potential has been assessed at several hundred EJ for microalgae and several thousand for macroalgae, however there are substantial uncertainties. Furthermore, many technical and economic challenges remain, which means that a significant contribution from algae will be realisable only in the longer term[16].

3.1 SWEDISH BIOMASS POTENTIAL

The Swedish potential for increased biomass extraction from agriculture and forestry can be summarised as follows based on up-to-date assessments (see Figure 4):[17]

- The most up-to-date potential estimates show that biomass production can increase by about 40-50 TWh/year under today's conditions, including technical restrictions and main ecological and economic restrictions, without direct competion with other agricultural and forestry production.
- These amounts of biomass can generate approximately 22 to 32 TWh transportation biofuel (together with external electricity, heat, solid biofuel, protein feed or other products), which is equivalent to approximately one third of today's use of petrol and diesel for road transport.
- The assessment is that within a 30 to 50 year period, biomass potential can increase by about 70-90 TWh/year, e.g. due to increased forest production as a result of climate change, increasing share of agricultural land available for energy crops, and general productivity improvements.
- A large part of the potential consists of forest-based raw materials, e.g. various forms of felling residues such as branches and tops, as well as thin stemwood. A certain amount of harvesting of stumps is possible, but limited by ecological restrictions. A significant proportion of biomass raw materials can also be derived from agriculture in the form of harvest residues, energy crops on fallow- and surplus land, as well as fast-

14. Edenhofer (2011).

15. Akhurst et al (2011).

16. Bauen et al (2009).

17. The potential assessments in the below section has been partially updated compared with the main report from 2013, above all with respect to the potential for stumps and the availability of arable land for energy crops in a long term perspective, see Börjesson (2016), Potential för ökad tillförsel och avsättning av inhemsk biomassa i en växande svensk bioekeonomi (in Swedish), Report no 97, Environmental and energy system studies, Lund Institute of Technology, Lund.

18. This potential does not include residual products from the forest industry (e.g. black liquor), as these would predominantly need to be replaced with other biomass in connection with a transition to transportation fuel production.

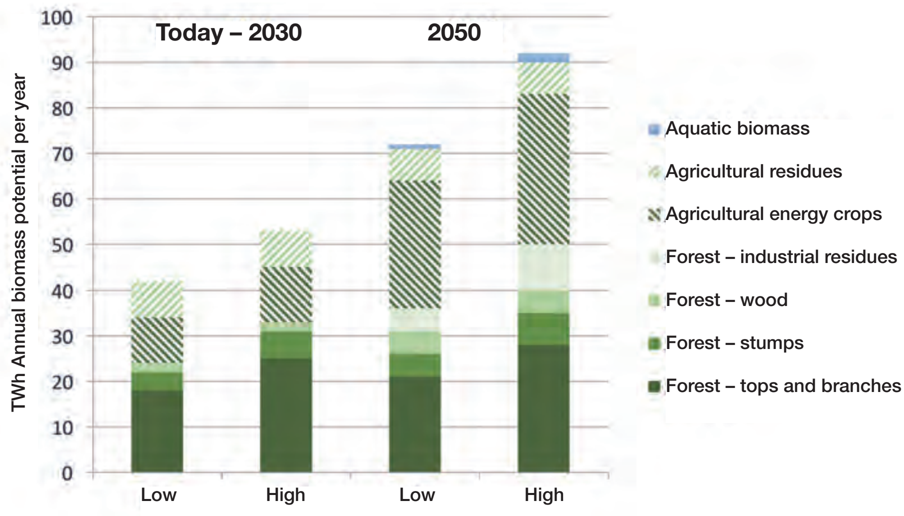

***Figure 4.** Estimated potential och increased biomass potential within Sweden, from forest, agriculture and aquatic systems from today until the year 2050 (based on Börjesson, 2016).*

growing hardwood trees on disused agriculture land. Furthermore, an increased amount of waste and residuals can be used for biogas production.

- Aquatic biomass for biofuel production from cultivation and harvesting of micro- and macro-algae is expected to contribute only marginally in Sweden in the foreseeable future, due to the limitations set by climate conditions

As a comparison, today's total annual forest growth in the form of stemwood, including branches and tops, as well as stumps, is equivalent to about 400 TWh, while today's annual total extraction of forest biomass is about 200 TWh. The equivalent total annual biomass production within Swedish crop cultivation is about 75 TWh, of which around 50 TWh is harvested.

There are also several possibilities for increased bioenergy production that have not been included in the above, e.g. a more adapted distribution of agricultural land in terms of crops and rearing live-stock, reduced food waste and reduced meat

There are differences in various studies compared with the compilation made above, due to them having e.g. different restrictions and time horizons. A common conclusion, however, is that there is a significant potential to increase the extraction of biomass from Swedish agriculture and forestry. However, the potential is distributed differently throughout the country, which must be taken into account in, for example, location of future fuel plants

3.2 ENERGY BALANCE AND GHG PERFORMANCE FOR RAW MATERIALS

Different raw materials from agriculture and forestry have different energy balances and GHG performances. For energy crops, the harvest levels vary between different geographical areas in Sweden, but also between different soils within the same area. In overall terms, the energy balance, expressed as energy harvest divided by energy required for cultivation and transport, is often about 10 for traditional agricultural crops and between 20 and 40 for energy forest plantations. Extraction of logging residues (branches and tops) has an energy balance of about 40. This means that the energy content in the raw materials is about 40 times higher than the energy needed for cultivation and transport. GHG performance largely follows the energy balance for the different crops and residual products, i.e. a high energy balance mostly means that GHG emissions are low[19].

Other important factors are whether the crops are annual or perennial and which type of land that is cultivated. Cultivation of annual crops on previously grass-covered land can lead to losses of land carbon, which impairs their GHG performance. On the other hand, if perennial energy crops are grown on previously grass-covered land, the land effects are marginal and if they are grown on already open arable land, carbon storage in the ground increases, which improves their GHG performance. Harvesting branches/tops and straw reduces the carbon content in the soil somewhat compared with when they are left in situ, i.e. including these direct land effects somewhat impairs their GHG performance.

19. SOU (2007); Börjesson et al (2010 och 2012).

Chapter 4

WTT performance for biofuels

Below is a summarised comparison between energy balance, GHG performance and costs for different transportation biofuel systems. These comparisons should be interpreted with great caution as different processes and production systems have different degrees of maturity, with some being commercially available while others are only available on a pilot and demonstration scale or are at the trial and development stage. For example, production systems for sugar cane-based ethanol have been developed and expanded commercially for some 30 years, while transportation biofuel systems based on lignocellulose are at the break of commercialisation. This means that factors such as production costs and energy efficiency must be estimated for an advanced and mature market, which substantially increases uncertainty regarding future scale benefits and learning effects. There is particularly large uncertainty when it comes to future costs.

The results are based on research studies and apply systems analysis from lifecycle perspective. In addition, the results are based on typical configurations of the respective process chain[20]. The values indicated can therefore differ considerably compared to those for specific, actual, production plants, as well as compared with the standard values that are used within RED, for example[21].

4.1 ENERGY BALANCE AND PRODUCT YIELDS

Energy balance for a process chain refers here to how much energy is supplied over and above the energy that the raw materials contain (from cultivation to finished fuel), in relation to the transportation fuel's total energy content. The same concept can also be labeled "external energy input". Below is an account of the energy balance, partially excluding indirect effects of alternative use of by-products from the production process, partially including indirect effects (system expansion). The indirect effects can be both positive, e.g. when digestate replaces mineral fertiliser through increase in recirculation of nutrients to arable land, or negative if the production process changes, e.g. so that by-products that are currently used as animal feed (e.g. draff and rapeseed cake) are excluded and have to be replaced by other feed.

The energy balance for different biofuels produced via different process chains is shown in Figure 5, on the next page. The results can be summarised as follows:

- The energy balance for fossil fuels is between 15 and 36%.
- The energy input in biogas production from crops and fertiliser is equivalent to 35-40% of the energy biogas's energy content, and over 50% when by-products that are currently used as fodder are utilised as raw material (i.e. including system expansion).
- The energy input in integrated ethanol plant systems based on lignocellulose where biogas is also produced is 15-20%. Biogas from waste products and sugar cane ethanol has approximately the same energy performance.
- The energy input for RME production is about 15% with system expansion and about 45% excluding system expansion. Rapeseed meal, which is an important by-product of RME production, delivers a substantial indirect energy gain when

20. Omfattande t ex både standardiserad livscykelanalys och industriell systemanalys, vars metodik skiljer sig åt i vissa avseenden.

21. Totala mängden referenser för detta kapitel är mycket stor, men omfattar för biokemiska processer t ex Lantz m fl (2009, 2012); Börjesson m fl (2009, 2010); Gissén (2012); Palm & Ek (2012); Prade m fl (2012); Tufvesson & Lantz (2012) och för termokemiska processer t ex Andersson m fl (2013); Heyne & Harvey (2013b); Ekbom m fl (2005, 2012); Fredriksson Möller m fl (2013); Gassner & Maréchal (2009); Johansson m fl (2012); Petterson & Harvey (2010); van Vliet m fl (2009), se vidare huvudrapporten.

22. HVO/HEFA baserad på solrosolja och palmolja uppskattas ha en energibalans kring 25-30%, exklusive systemutvidgning.

it is used and replaces other protein feeds. The energy balance for RME can be compared with the energy balance for HVO based on rapeseed, which is estimated at 35-40% excluding system expansion.

- Grain ethanol and ethanol from sugar beet has an energy input equivalent to about 50%. However, this is lower if production takes place in integrated plants or when straw and sugar beet leaves are used as fuel in the process.

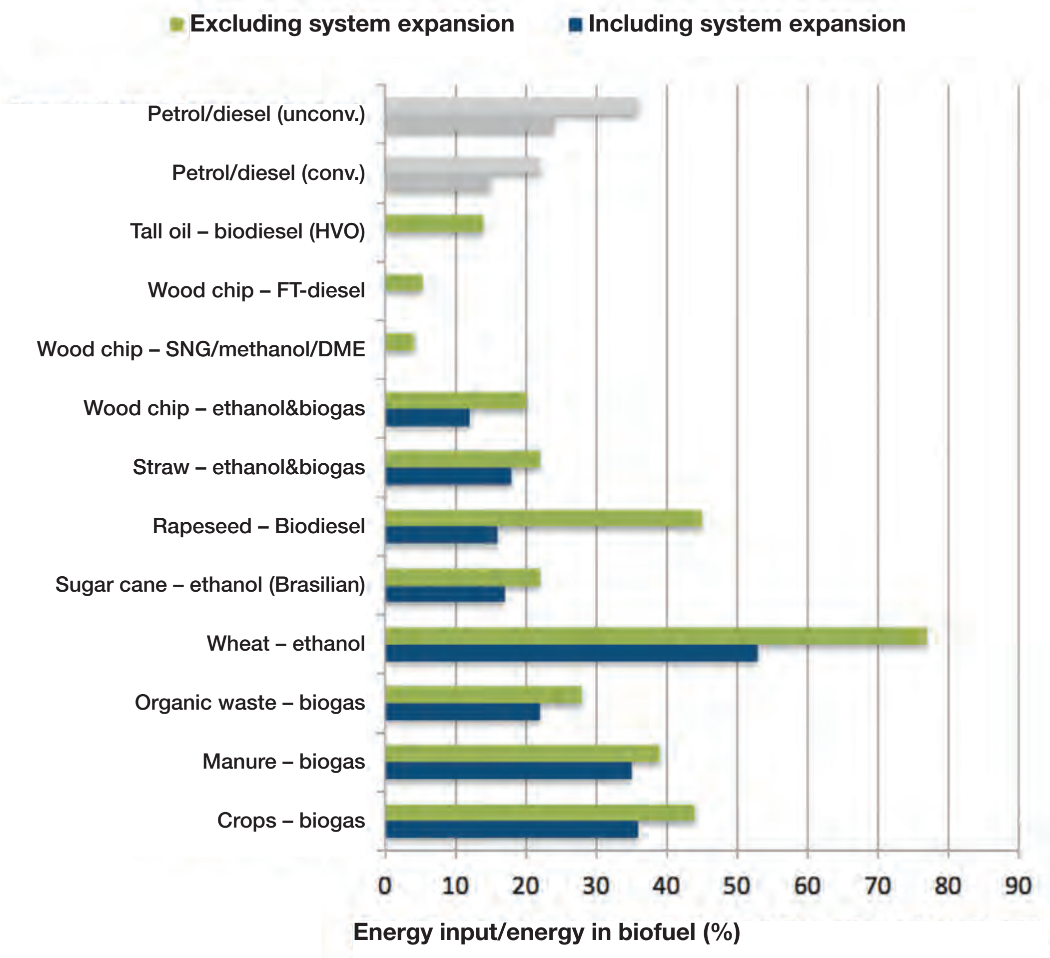

Figure 5. *Energy balance for production system for biofuel with and without system expansion. As a comparison, the energy balance for petrol and diesel is also shown when conventional, and respectively, unconventional, fossil raw materials are used.*

- The external energy input is lowest for ligno-cellulose-based transportation fuel via thermal gasification and is equivalent to 4-5% of the transportation fuel's energy content when wood chips are utilised as raw material, and respectively 7-10% when willow is utilised.

Positive indirect effects in connection with system expansion consist of replacement of protein feeds with the by-products obtained from ethanol production from crops, respectively, net surplus of electricity with production of sugar cane ethanol, as well as external utilisation of surplus heat from integrated ethanol plants based on lignocellulose. For biofuel produced from ligno-based raw materials via thermal gasification, system expansion normally entails a minor change as the net surplus of electricity and externally useable surplus heat is assumed to be marginal as the fuel yield is maximised.

When it comes to RME and grain ethanol, which generates, respectively, rapeseed meal/cake and draff, the energy balance is impaired if these by-products are not used as feedstuffs, e.g. in a saturated protein fodder market. On the other hand, these by-products can then be used as raw material to produce biogas. This means that these production systems can retain a relatively unchanged energy balance thanks to co-production of liquid fuel and biogas, instead of liquid fuel and feed.

Another way of calculating energy efficiency for different biofuel systems is to determine the product yield as a proportion of biomass supplied. Besides the primary product, biofuel production also usually generates a number of by-products such as electricity, steam and/or hot water, for example. Other products can also be extracted, for example, tall oil in connection with the integration of solid fuel gasifiers in pulp mills, or natural gas with integration in oil refineries. This differentiates the yield if consideration is paid solely to the production of fuel or if the energy value for all products is included (total energy efficiency).

Transportation fuel yield and total energy efficiency for different biofuel systems can be summarised as follows:

- For gasification-based fuel, bio-SNG generally produces the highest fuel yield (64-70%). However, compressor- and distribution work is not included, the inclusion of which would have a negative impact on total product yield from well to tank (for gaseous compared with liquid fuels).
- Bio-methanol production via gasification produces a fuel yield of 57-67%. Bio-DME is produced through dehydration of methanol, and normally produces a slightly lower yield (56-66%)
- FT fuel produces lower yields (50-57%) than the above-mentioned fuels. However, FT synthesis results in at least two different products (synthetic diesel and FT wax). If only the yield of synthetic diesel is taken into consideration, an even lower product yield is obtained[23].
- Ethanol via fermentation of synthesis gas produces by far the lowest fuel yield (about 25%).
- For combined biochemical production of ethanol and biogas, based on lignocellulose, the total fuel yield varies between approx. 40% (if only ethanol is produced) and approx. 65%.
- The total energy efficiency is generally highest for industrially integrated biofuel gasifiers, in particular black liquor gasification, which delivers the highest efficiencies for most types of biofuels.

23. Data for production of methanol, DME and FT diesel are updated compared with the main report. New data is drawn from Hannula, I & Kurkela, E (2013), Liquid transportation fuels via large-scale fluidised gasification of lignocellulosic biomass, VTT Technology 91, Finland.

- Combined production of ethanol and biogas also entails high total efficiencies, particularly if this is based on wood chips or hemp.
- Stand-alone plants generally deliver lower total energy efficiencies (ethanol production via gasification has a particularly low efficiency).

There are several different ways to calculate energy system efficiencies. If the production system includes different types of product flows and forms of energy, conversion to so-called electricity equivalents can be used for comparing different systems. This method includes consideration of quality differences between energy carriers. For some production cases where the net electricity balance is impaired (for example, based on black liquor gasification), the method produces a relatively lower efficiency. However, the conclusion remains that industrially integrated systems, in particular black liquor gasification, are most effective for production of transportation biofuel.

4.2 GHG PERFORMANCE AND ARABLE LAND EFFICIENCY

The GHG performance for different transportation biofuel systems has been calculated in part according to the regulations in RED and in part based on the ISO standard for lifecycle analysis[24], which recommends a calculation methodology that applies system expansion. The latter implies that both positive and negative effects of production of by-products should be taken into consideration in the calculation. In addition, direct land use effects (dLUC) are included with system expansion, but not, on the other hand, indirect land use effects (iLUC).

GHG performance for different transportation biofuels produced from different process chains is set out in Figure 6 below. The results can be summarised as follows:

- According to RED, emissions of GHGs from fossil fuels (petrol and diesel) are currently on average about 84 g CO_2 equivalents per MJ, of which about 13-16% comprise emissions from extraction, refining and transportation.
- If new, unconventional, fossil raw materials start to be used for transportation fuel production, e.g. shale gas, oil sands and carbon, fuel cycle GHG emissions can increase by up to 100%.
- Calculations based on system expansion show that biogas from fertiliser and waste produces the greatest reduction in GHGs. The emissions are often negative, due to indirect GHG gains from reduced methane emissions from respectively, conventional fertiliser storage and replacement of mineral fertiliser. According to RED, they amount to between 7 and 15 g CO_2 equivalents per MJ upgraded biogas.
- Biofuel based on gasification, HVO from tall oil, biogas from ley crops and combined ethanol and biogas production from lignocellulose produces a reduction in GHGs of 80-95%.
- The reduction in GHGs for HVO from animal fat, RME, sugar cane ethanol, biogas from crops and wheat-based ethanol is 65-80%, including indirect gains from by-products.

When system expansion is applied, GHG benefits for ethanol from crops and for RME are improved, thanks to indirect gains from the animal feed by-products that are generated. The GHG benefit can further increase if, for example, carbon dioxide that is generated in ethanol production is separated and stored. On the other hand, GHG performance is impaired somewhat for fuel based on straw and wood chips, as harvesting these residual products reduces the content of land carbon slightly.

24. *ISO (2006)*

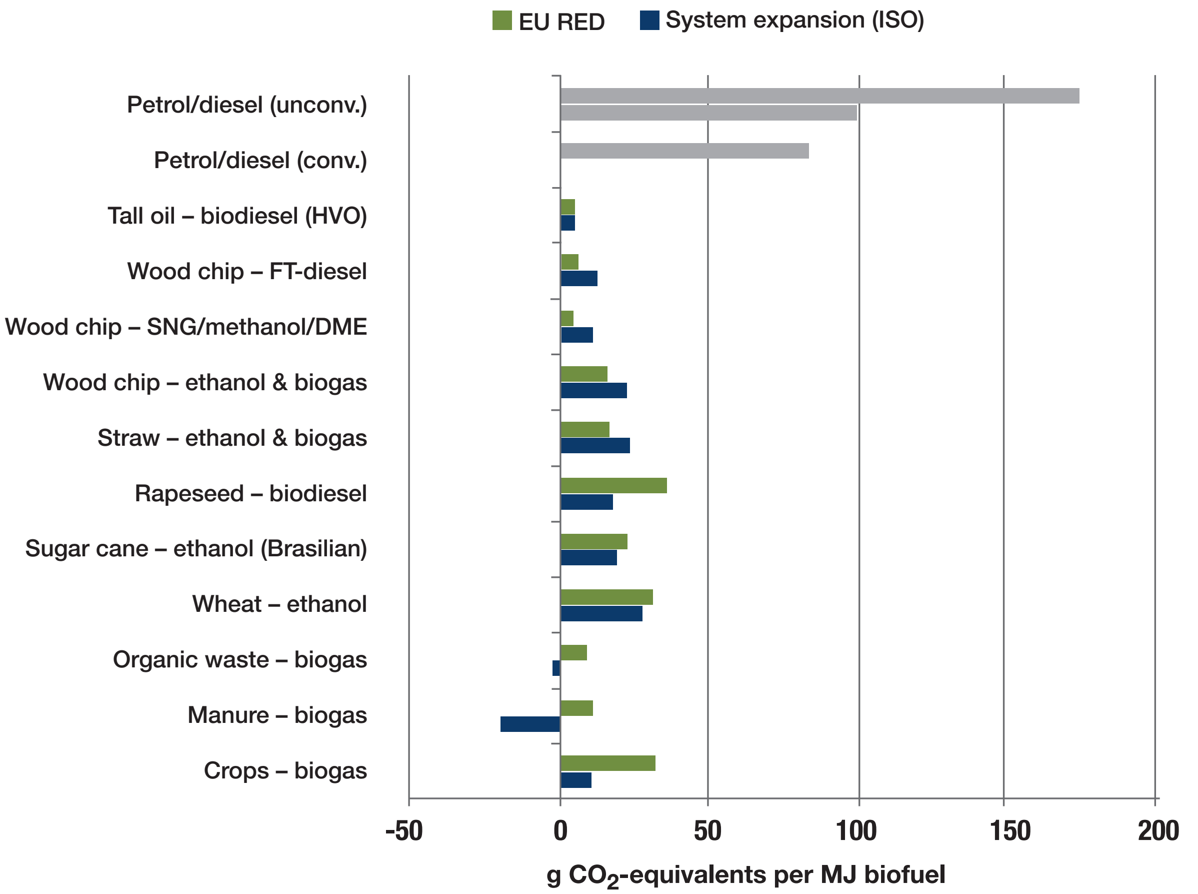

Figure 6 *GHG performance for different biofuel production systems calculated according to the methodology in respectively, the EU's Renewable Energy Directive (RED) and the ISO standard for lifecycle analysis (system expansion). As a comparison, GHG performance is also shown for petrol and diesel according to RED's comparison value, and, respectively, if unconventional fossil raw materials are used*[25].

25. *An important factor for biogas's greenhouse gas performance is the amount of methane slip. The calculations here are based on well-functioning systems where methane emissions amount to a maximum of about 1.5%. Emissions in today's biomethane production plants are usually estimated to vary between less than 1% up to 3%, although individual plants can have even higher emissions.*

Transportation fuel yield per hectare and year for different production systems is particularly relevant for the discussion about direct and indirect land use effects in production of biofuel from raw materials cultivated on arable land – where high yields naturally reduce the risk of, for example, iLUC.

Ethanol from sugar cane (produced in Brazil) and biogas from sugar beet (including tops) has the highest fuel yield per hectare of arable land and year, approximately 160 GJ. SNG via gasification of willow and combined ethanol and biogas production from willow in integrated ethanol plants, both have yields of about 120 GJ. There are a number of systems that generate about 100 GJ fuel per hectare and year, such as biogas from maize and rye, ethanol from sugar beet, ethanol and biogas from hemp, SNG from hybrid aspen and methanol, DME and hydrogen gas from willow. Examples of systems that generate about 80 GJ fuel per hectare are biogas from wheat and grass, methanol and DME from hybrid aspen and FT diesel from willow. Ethanol from wheat generates around 70 GJ and RME from rapeseed just under 50 GJ fuel per hectare and year. However, these systems also generate 1 tonne of protein per hectare and year, which produces an indirect arable land saving in that there is a reduction in the need to cultivate protein feeds. If this indirect land saving is included, the arable land efficiency for grain ethanol and RME is considerably improved.

The reduction in GHGs per hectare and year for different arable land-based biofuel systems can to a large extent be related to fuel yield per hectare and year, where a level of 100 GJ/ha per year is roughly equivalent to 7 tonnes of CO_2 equiv per ha and year. One difference is that biofuel based on energy forest increases its GHG benefit in comparison with biofuel based on traditional crops.

4.3 PRODUCTION AND DISTRIBUTION COSTS

Comparisons between production costs for existing biofuel systems and those which are not yet on a commercial scale should be interpreted with great caution, as there is considerable uncertainty, especially for future commercial plants.

Estimated production costs for biofuel produced from different process chains is set out in Figure 7 below, and can be summarised as follows:

- The production cost for petrol and diesel is currently judged to be around SEK 4 per litre (2016). Including Swedish CO2 tax, the cost is about SEK 7 per litre[26].
- The production cost for Brazilian sugar cane ethanol, including transport to Europe, is currently estimated to be around SEK 5 per litre of petrol equivalents.
- Upgraded biogas based on residual products and waste is normally estimated to cost under SEK 5 per litre of petrol equivalents to produce.
- The production cost for grain ethanol and RME is calculated to be about SEK 7 per litre of petrol equivalents, which is also valid for upgraded biogas from crops and liquid manure, respectively.
- For bio-based vehicle gas from manure and residual products, the investment cost is most significant, while raw material cost and price for by-products are the most important factors for grain ethanol, RME and biogas derived from crops.
- Future production costs for fuel from lignocellulose produced, respectively, via gasification and in integrated ethanol plants are also estimated to be around SEK 7-8 per litre petrol equivalents for the most cost-effective process concepts. Gasification of black liquor is deemed to produce lower production costs[27].

26. Updated assessment based on current oil price level for 2016.

27. Figure 6 does not include production costs for biofuel from black liquor via gasification. However, the literature shows that production of methanol, DME and FT diesel via black liquor gasification entails lower costs than if solid biofuel is gasified (see in addition the main report).

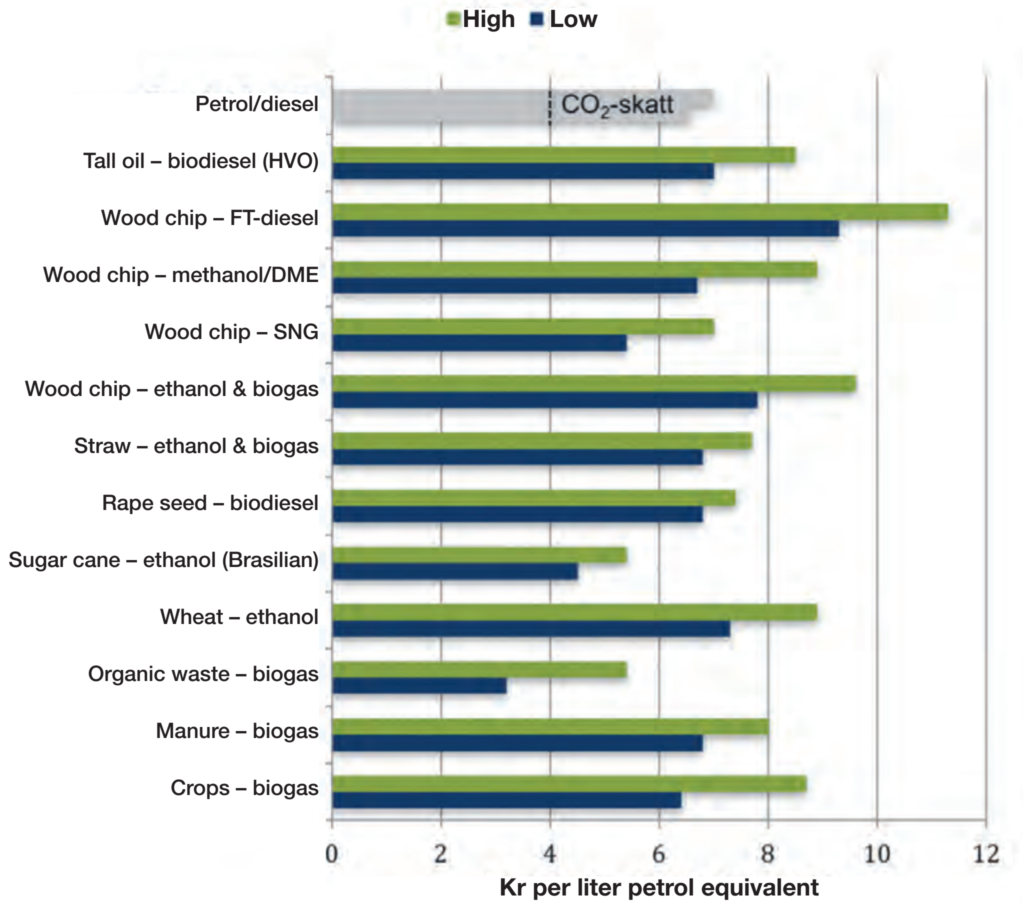

Figure 7. *Estimated production costs for different biofuel systems, expressed as SEK per litre petrol equivalents. Respectively, low (blue) and high (green) bar illustrate possible variations in raw material costs (biogas, RME and ethanol from crops), alternatively process design (integrated ethanol plant and transportation fuel via thermal gasification). The degree of uncertainty in the production costs is indicated by, respectively, * = minor uncertainty, ** = some uncertainty, ***= great uncertainty [28]. As a comparison, the estimated production cost for petrol and diesel including CO_2 tax (2016 cost level) is also presented.*

28. To increase the comparability of production costs for biofuel from lignocellulose, in Figure 7 studies are used that as far as possible are based on comparable conditions, Swedish circumstances and are current, e.g. in respect of updated raw material costs (Börjesson et al, 2013, Ekbom et al, 2012). For gasification, this means that the results have been used primarily from one study (Ekbom et al, 2012). In addition, an uncertainty interval has been added (respectively low and high bar) to reflect possible differences in process design and product yield.

- SNG is estimated to have somewhat lower production costs, about SEK 6 per litre petrol equivalents, while FT diesel is judged to have considerably higher, about SEK 10.
- The investment cost dominates in transportation fuel systems based on lignocellulose, however, changed raw material costs are also of relatively major significance.

The differences in scale between different production systems are significant, from biogas plants of 5-7 MW to gasification plants of 200-300 MW, and with other plants falling somewhere in between. The investment costs can thus differ between, for example, SEK 60-70 million for a biogas plant up to SEK 4-6 billion for a large-scale gasification plant. Thus, the financial risks for an investor in a gasification plant are much greater. Besides financial risks, there are also technological risks to take into consideration. These risks are greater for production systems that are not commercial today, e.g. gasification plants and large-scale integrated ethanol plants based on lignocellulose, but also for those systems that are more closely integrated with existing processes, such as black liquor gasification. Higher financial and technical risks normally imply that the demands for risk compensation increases from the investor's point of view.

The physical properties of the fuel also influence the distribution costs to the end user as well as associated to the handling at the filling station. In general, liquid fuels have lower distribution costs than gaseous ones. However, this does not apply if gas infrastructure is already widely available. In that case, considerably lower distribution costs are obtained for gaseous fuels.

A rough estimate of the cost associated to distribution and handling at filling stations for petrol and diesel is SEK 1-1.5 per litre. Corresponding costs for FT diesel and mixed biofuel areestimated to be at about the same level. Methanol and ethanol, on the other hand, are estimated to have approximately 20-30% higher costs, due to lower energy density in these fuels. DME, as well as SNG, fall into the higher cost range. For SNG an estimate has been made of approx. SEK 2 per litre for SNG, while the costs for DME distribution are harder to estimate as new systems are needed. Finally, hydrogen gas is the most challenging fuel to distribute and store.

Energy use for distribution of transportation fuel also differs. The energy requirement for distribution of liquid fuel is approx. 1% of the transportation fuel's energy content. For methane and hydrogen gas, additional electricity is required (for compression etc.) equivalent to approx. 3 and 6% respectively of the fuel's energy content[29]. Liquefaction of hydrogen gas by cooling implies an energy loss of about 30% of the hydrogen gas's content[30].

29. However, for biogas this energy input has been included in the calculations of GHG performance, presented in Section 4.2.

30. Concawe (2007) and Vätgas Sverige (2013).

Appendix I
Swedish biofuel production plants

Below follows a compilation of existing pilot, demonstration, and commercial plants (in 2016) for transportation biofuel production in Sweden, based on information available to the authors. Moreover, a selection of plants currently in a planning stage is presented. In addition to these plants, there are plans for maybe another five or six large-scale plants, but there are no specific start-up years currently communicated.

THERMOCHEMICAL PLANTS

Existing pilot and demonstration plants

Plant	Technology	Feedstock	Output(s)	Status
LTU Green Fuels, demonstration	Pressurised (30 bar) entrained flow gasification, 3 MW fuel	Black liquor, pyrolysis liquid	DME (synthesis plant-, capacity 4 tonnes/day); Methanol	Start year 2005. In operation (>26 000 hours)
GoBiGas, Göteborg, demonstration	Indirect gasification, 20 MW produced gas.	Wood pellets (wood chips since March 2016)	SNG delivered to gas grid	Start year 2014. Gasification >4 000h during 2015.
PEBG, SP ETC/BioGreen, Piteå, pilot	Pressurised (15 bar) entrained flow gasification 1 MW fuel	Forest residues, torrefied biomass	Syngas	Experimental campaigns are executed regularly
Chalmers, Göteborg, pilot	Indirect gasification (atmospheric bubbling fluidised bed), 2 MW.	Wood pellets	Syngas	Start year 2007. Experimental campaigns are executed regularly
WoodRoll, Köping, pilot	Indirect gasification, 500 kW fuel	Wood chips	Pure syngas	Start year 2015 (integrated).

Planned plants

Plant/Type	Technology	Feedstock	Output(s)	Status
GoBiGas, Göteborg, Phase 2, commercial	Indirect gasification, 80-100 MW	Wood fuel	SNG	Abandoned
RenFuel, Bäckhammar, pilot	Depolymerisation and hydrotreatment of sulphate lignin, 9 tonnes fuel/day	Lignin from black liquor	Lignin oil => renewable diesel/petrol	Scheduled for commissioning in the beginning of 2017
SCA, Umeå, pilot	Depolymerisation and hydrotreatment of sulphate lignin	Lignin from black liquor	Lignin oil => renewable diesel/petrol	Scheduled for commissioning during 2017
Chemrec/Domsjö Örnsköldsvik	Pressurised entrained flow gasification	Black liquor	Approx 960 GWh of DME or methanol per year	Abandoned

BIOCHEMICAL PLANTS

Existing commercial plants

Plant	Technology	Feedstock	Output(s)	Status
Lantmännen Agroetanol, Norrköping	Fermentation	Cereal, residues (starch based)	Ethanol (260 000 m^3/year (approx 1535 GWh/year)	Commercial operation
Aditya Birla, Örnsköldsvik	Fermentation	Residues from sulphite pulp production	Ethanol (15 000 tonnes/ year in total)	Start year 1940. Only a small share is used for transportation biofuel.
A total of 277 plants around Sweden	Digestion (277 plants) and upgrade (59 plants.)	Domestic waste, waste water etc.	Biomethane (1 784 GWh/year, in total)	Commercial operation. 57% is upgraded to biofuels.
Etanolix 2-0, St1, Göteborg	Fermentation	Food waste	Ethanol (capacity 5 000m^3/year)	Inaugurated in June 2015.

Existing pilot and demonstration plants

Plant	Technology	Feedstock	Output(s)	Status
Sekab/SP (Biorefinery Demo Plant)	Fermentation	Different types of cellulose	Ethanol (capacity 500 litres/day)	Inaugurated in 2004. In totalt, 50 000 hours of operation
PDU, Lund University	Pretreatment and fermentation	Different types of cellulose	Ethanol (20-100 litres/day)	Experimental campaigns are executed regularly

Planned plants

Plant	Technology	Feedstock	Output(s)	Status
Network Biogas, Karlshamn	Digestion and upgrade	Cereals/ cellulose	SNG (initially 970 GWh/ year, thereafter gradual expansion to double capacity)	Planned start for main production facility in Karlshamn in 2016.

OLEOCHEMICAL PLANTS

Existing commercial plants				
Plant	**Technology**	**Feedstock**	**Output(s)**	**Status**
SunPine/Preem	Production of crude tall diesel at SunPine and final hydrogenation at Preem's refinery	Tall oil (residual product from pulp plants)	HVO diesel fuel	Start 2010. With capacity of 100 000 m^3/year (Sunpine and Preem); from 2015 200 000 m^3/year (Preem)
Perstorp, Stenungsund	Esterification	Rapeseed oil, biomethanol	RME (150 000 tonnes/year)	Start year 2007. For low-level blends and B100
Energigårdarna, Karlshamn	Esterification	Rapeseed oil	RME (500 GWh/year)	Start year 2006

Appendix II

International biofuel production plants

Below follows a few examples of recently constructed plants for production of biofuels for transportation to illustrate some important development paths, seen internationally during the last couple of years. The examples only refer to production based on previously non-commercialised technology, i.e. process chains other than digestion, production of FAME through esterification, or fermentation of sugar or starch-based feedstocks

Thermochemical conversion

In the field of gasification of lignocellulosic materials, in addition to Sweden, e.g.Canada and Austria have been successful. Among the few examples of large-scale production plants are:

- Enerkem (Alberta, Canada) with gasification of waste for production of ethanol and methanol (38 million litres/year), whichwas commissioned in late 2015 (status uncertain), based on the same technology as the demonstration plant in Westbury (operational since 2009).

Biochemical conversion

Fermentation of cellulose has had the strongest development in countries with a large conventional ethanol production (Brazil and the USA) and has been focused on agricultural crop residues (corn cobs, leaves, husk and stalk, bagasse, and straw). The development took a major step forward in 2013/2014 when several large-scale plants were inaugurated:

- Royal DSM/Poet (Emmetsburg, Iowa, USA), fermentation of corn cobs, leaves, husk and stalk, capacity of 75 million litres of ethanol per year, start year 2014
- Raizen/Iogen (Piracicaba, Brazil), fermentation of sugarcane straw and bagasse, capacity 40 million litres ethanol per year, start year 2013.
- Beta renewables (Crescentino, Italy), fermentation of agricultural crop residues (straw), capacity of 75 million litres of ethanol per year, start year 2013
- Abengoa (Hugoton, Kansas, USA), enzymatic hydrolysis and fermentation of corn residues, capacity of 95 million litres of ethanol per year, start year 2014, abandoned December 2015.

Oleochemical conversion

The expansion of oleochemical conversion currently mainly focuses on production of renewable diesel from hydrotreatment of oil based feedstock (HVO). Neste Oil is the largest player on the market, producing 1.6 million tonnes of HVO per year from their plants in Finland, Rotterdam and Singapore. Examples of other recently constructed production plants are:

- UPM (Laapeenranta, Finland), hydrotreatment of crude tall oil to renewable diesel (HVO), capacity of 120 million litres per year, start year 2015.
- ENI (Porto Marghera, Italy), hydrotreatment of vegetable oils to renewable diesel (HVO), capacity of approx. 360 000 litres per year, start year 2014.

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