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Production of liquid advanced biofuels - global status

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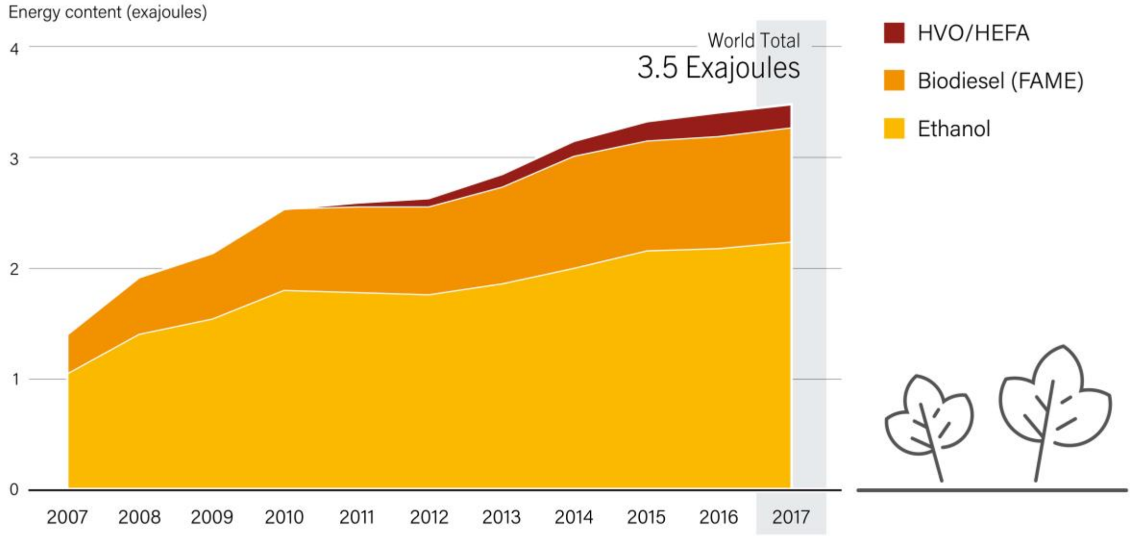
EXECUTIVE SUMMARY

This study provides an overview of current and future global production of liquid biofuels for use in the transportation sector – with a special focus on advanced liquid biofuels. The study is made by CIT Industriell Energi on assignment of the Norwegian environment agency.

The overview is based partly on statistics of historical and current global biofuel production in general, partly on a thorough mapping of existing and planned production plants that may be able to contribute to advanced liquid biofuel production in the period from now until the year 2030.

Based on data from REN21 Renewables 2018 (below), total global biofuel production amounted in 2017 to about 970 TWh, of which 623 ethanol, 284 conventional biodiesel and 61 TWh HVO (about 105, 31 and 6.5 Mm^3, respectively). Ethanol production is dominated by the US and Brazil, while biodiesel production is more spread between regions and countries. In statistics for biofuel production, the amount of advanced biofuels are in general not specified separately.



In this report focus is on the production of *advanced biofuels*. The definition used is the one used e.g. by the EIA, namely that advanced biofuels are biofuels produced from lignocellulosic feedstocks (i.e. agricultural and forestry residues), non-food crops (i.e. grasses, miscanthus, algae) or industrial waste and residue streams, which also are associated with high GHG reductions and that are assumed to be able to reach zero or low iLUC impact.

Many reports and studies of development trends for advanced biofuels aim to support the definition of required policy action or technological development, and therefore focus on advanced biofuels produced by novel production technologies. Here, the main focus is instead to describe the potential availability of advanced biofuels in the relatively limited time period from now until 2030. It is therefore important to note that advanced biofuels can be produced also in commercially mature technological value chains. Further, it is important to understand that the system linkages and flexibility properties of different value chains vary.

From the inventory of existing plants that produce advanced biofuel, the total amounts of advanced liquid biofuels produced in 2016/17 have been estimated to about 27 TWh/year (about 3.0 Mm^3/year), excluding production based on PFAD as feedstock. This equals less than 3 % of total biofuel production and, thus, less than 0.1 % of total current energy use for transportation. If PFAD is classified as a waste based feedstock the total amount is instead estimated to about 40 TWh/year (about 4.3 Mm^3/year). In 2018, additional production of about 3.5 TWh is expected to come on line. Notably, 96-97 % of the advanced biofuels estimated above consists of HVO, which makes the estimate extremely sensitive to assumptions about this value chain. In this estimate, other advanced biofuels (i.e. ethanol) amounts to only about 1 TWh (0.16 Mm^3). The IEA estimates global *novel* advanced biofuel production in 2017 to about 3.5 TWh, which thus is considerably higher.

Based on the type of plants that have been built and for which there are actual plans for construction of large-scale plants, four different technological value chains have been in focus. For each of these, the status in terms of both existing and planned plants are described. For this inventory the IEA databases and the SGAB reports have been utilized, together with a large number of other sources. In total, 28 operational plants and 42 planned plants (including expansions of existing plants) have been identified. In addition to this number, twelve plants are planned in India. However, plant specific information is unavailable for these plants.

Gasification for the production of liquid biofuels

Only one plant, by Enerkem in Canada, is operational, producing ethanol from municipal solid waste. There are seven planned plants identified, aiming to produce ethanol, methanol or diesel with a total capacity of 7.5 TWh (0.9 Mm^3). Two of these are also by Enerkem, and two others currently under construction.

Gasification is a technology associated with high flexibility on both the raw material and product side – which in the longer term is favorable for the pathway – however, it seem to have had a decreasing momentum lately.

Fermentation for the production of alcohols (primarily ethanol)

There are nine operational plants based on cellulosic feedstock, of which three in China and three in Brazil (one very small). In the US, several plants were built between 2012 and 2016, but all but one has since been closed down. The total capacity of operational plants is 2.3 TWh (0.4 Mm^3), but utilization rates are currently low. In addition there is advanced ethanol production from waste material, such as corn kernel fibre (cellulosic) and bread (starch).

There are 13 planned plants for ethanol production based on cellulosic feedstock such as wood, crop residues etc, with a total capacity of 5.6 TWh (0.9 Mm^3), two of which in the Nordic countries and three in other parts of Europe.

Internationally, there is a continued strong focus on ethanol and on developing production capacity for advanced ethanol. In India, for example, there are plans for twelve smaller plants within the next few years (in addition to the 13 plants mentioned above).

Hydrotreatment of fatty acids for the production of HVO

The plants for HVO production are larger-scale and in total, 14 plants have been identified. However, only part of the production can be classified as advanced biofuels. The advanced biofuel production has been estimated to about two-thirds (40 TWh) of total production, if including PFAD as advanced feedstock, and less than half (about 25 TWh) if not.

The plans for additional HVO capacity are also large-scale – in total about 70 TWh (74 Mm^3) additional capacity is planned, divided between 13 plants (including expansion projects at existing plants). Several of those industries that now operate plants plan to expand, and new actors emerge. In the last group companies associated with the forest industry, focusing on new feedstock, are included.

In the Nordic countries, three of the plants above specifically claim that they will use wood residues and black liquor as feedstock and two more will base their production of a mix of tall oil, other waste oils and bio-oils (see below) only. These five plants are planned for a total capacity of 24 TWh.

Thermochemical conversion for the production of intermediate bioenergy carriers

It should be noted, that the plants for production of intermediate bioenergy carriers do not add to total biofuel production capacity, but rather aim to expand the feedstock portfolio for the plants above.

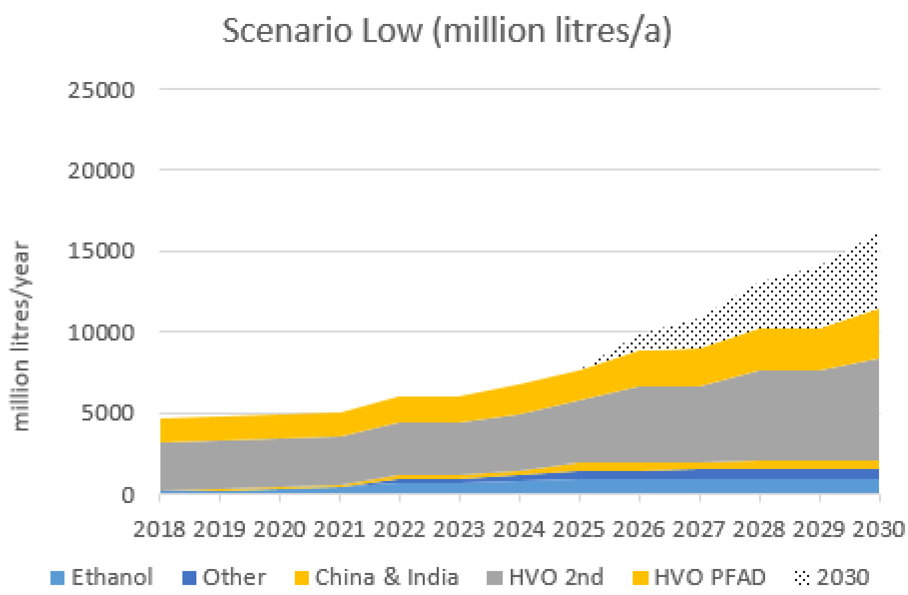
There is currently one plant for pretreatment of tall-oil (for the production of HVO) and three fast pyrolysis plants for production of bio-oil (currently used for heat and power generation) in operation.

Developments are ongoing to improve the quality of bio-oils produced with fast pyrolysis and to develop other types of liquefaction technologies that can produce oils that can be included in the refinery process in similar ways as current feedstocks for HVO. For the development of fast pyrolysis, Ensyn is a major player. In the development of other liquefaction technologies several companies in the Nordic countries are active. In total, nine planned plants (including expansions of existing plants) have been identified in this value chain.

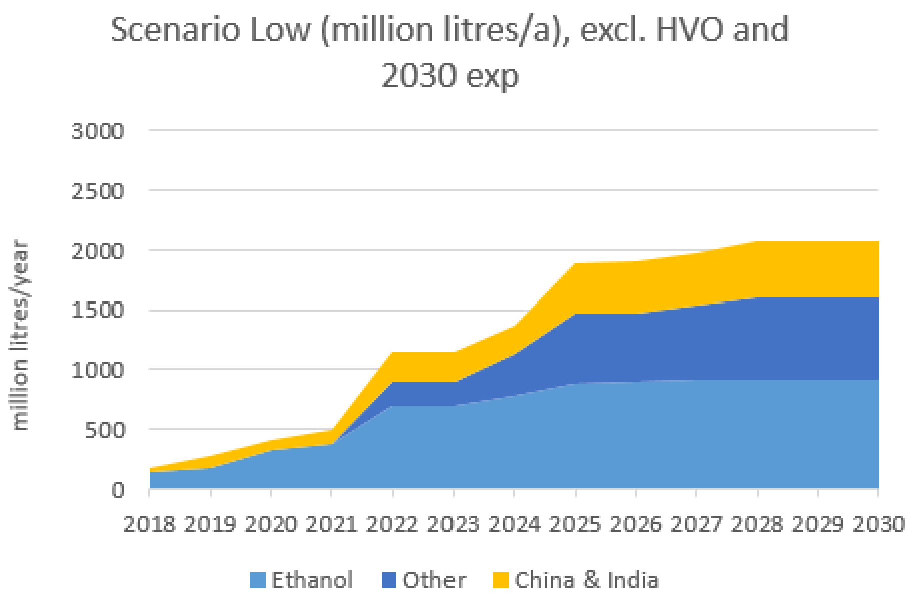
Finally, the data on large-scale existing, idle and planned production plants have been used to make an estimate of the potential development of advanced biofuel production from now until the year 2030. This estimate is based on generalized assumptions regarding the realization and operation of plants, and not on a complete scenario or modelling analysis. Two scenarios – high and low - are investigated. In Scenario High, all planned production plants are assumed to be completed on time and operate at full capacity from the commissioning year. Additionally, all idled plants are assumed to resume operations at 100 % capacity. In Scenario Low, more conservative assumptions are made. In this scenario not all the planned production capacity is realized (either because plants are not built, or because they cannot reach full production), some plants may be delayed and only 50 % of idled plant capacity resume operations. A full description of the assumptions made for the two scenarios is given in Section 5.2.

In Scenario Low, the total amount equals about 54 TWh of advanced biofuels, or 39 TWh without fuel based on PFAD as feedstock, in 2023 and almost 104 and 74 TWh, respectively, in 2030. The 2030 levels would in volumes be equal to about 6.3 Mm^3 HVO (without PFAD based HVO), 1.4 Mm^3 ethanol and 0.68 Mm^3 other fuels mostly based on thermochemical conversion (assuming also these are some kind of diesel-like fuels). The expansion is illustrated in the figure below, and the numbers given above exclude the dotted area in the figure. Plans for production plants with start-up years after 2025 is difficult to find, and the dotted area represents an assumed continued expansion after 2025 at similar rates as the expansion in the years leading up to 2025. The production represented by the dotted area is however not based on the plant inventory.

The large increase in advanced HVO production can be compared to an estimate by the IEA that availability of waste oils and fats (probably including PFAD) may allow for HVO from these feedstocks to cover 6-8 % of global biofuel production, equaling about 58-78 TWh.

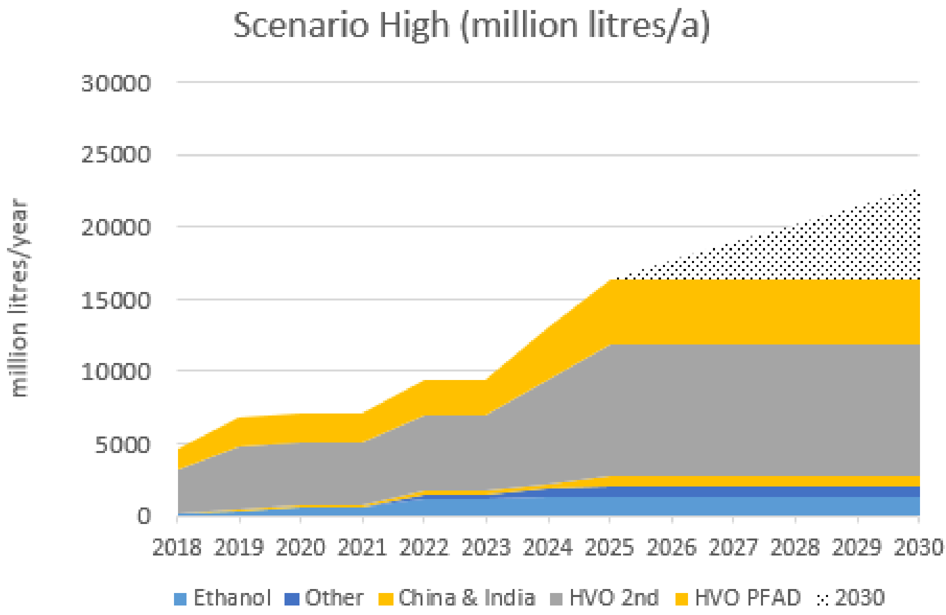


The production of advanced biofuels other than HVO consists of ethanol production based on fermentation of lignocellulosic feedstocks and the production of mostly FT-diesel and through diesel-like fuels trough gasification ("other" in figure below). The plants planned in China and India also consist mainly of advanced ethanol production.



The production excluding HVO equals about 2.1 Mm^3 (14 TWh) in 2030. This estimate can be compared to data from IEA studies, which give a prognoses of 11-18 TWh of novel advanced biofuels (excl. HVO) until 2030, while stating that in the longer-run (2050) biofuel production needs to increase to about 8 000 TWh (29 EJ), of which the major share consists of advanced biofuels (including HVO type fuels).

Scenario High represents a maximal case, and is considered less realistic then Scenario Low. This scenario assumes that all planned production plants are commissioned and start producing at full capacity in the planned start-up year, and that currently idled plants resume operations at full capacity. The total amount is equivalent to about 9.4 Mm^3 (85 TWh), or 6.9 Mm^3 (61 TWh) without fuel based on PFAD as feedstock, in 2023 and about 16.4 (149) and 11.9 Mm^3 (106 TWh), respectively, in 2030. The expansion of production levels for Scenario High is illustrated in the figure below. The numbers given above do not include the dotted area in the figure. This area represents a continued expansion after 2025 at similar rates as before, but is not based on specific plans for production plants. For the early years of the period, Scenario High is expected to almost certainly overestimate development, since it is quite unlikely that all plants are realized and produce at maximum capacity. Towards the mid-twenties and later, new development plans can evolve, and more plants be constructed. This might be especially true in areas like India and China where we now see increasing ambitions but so far few details on concrete plans.



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Executive summary ...ii
1 Introduction ... 1
1.1 Purpose and scope ... 1
1.2 The report ... 1
1.3 Definitions ... 2
2 Global production of biofuels ... 3
2.1 Data collection ... 3
2.2 Total global production of biofuels – historical overview ... 3
2.3 GLobal production of ethanol ... 5
2.4 Global production of biodiesel ... 7
3 Value chains for production of advanced biofuels ... 10
3.1 The concept of technology value chains for advanced biofuel production ... 10
3.2 Value chains used in this report ... 12
3.3 Relevance of system linkages and technology flexibility ... 13
4 Global production of advanced liquid biofuels ... 16
4.1 Data collection ... 16
4.2 Existing and operational plants and production ... 17
4.2.1 Plants based on the value chain for gasification ... 17
4.2.2 Plants based on the value chain for fermentation into alcohols ... 17
4.2.3 Plants based on the value chain for hydrotreatment of fatty acids ... 19
4.3 Idle and planned large-scale plants ... 21
4.3.1 Plants based on the value chain for gasification ... 21
4.3.2 Plants based on the value chain for fermentation into alcohols ... 23
4.3.3 Plants based on the value chain for hydrotreatment of fatty acids ... 26
4.3.4 Plants for the production of intermediate bioenergy carriers ... 28
5 Global advanced liquid biofuel production from now until 2030 ... 31
5.1 Estimate of current advanced biofuel production ... 31
5.2 Methodology for estimating future production ... 33
5.3 Estimate of potential based on plans for plant development ... 35
5.4 Global and European demand for advanced biofuels in 2030 ... 38
5.5 Status of development – in summary ... 40

References 42
Appendix A Global biofuel production volumes 1
Appendix B Value chains 1
Thermochemical value chains 1
Biochemical value chains 3
Oleochemical value chains 5
Appendix C Plant data for advanced biofuel production 1
Appendix D Additional figures 1

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

The purpose of this study is to provide an overview of current and future global production of liquid biofuels for use in the transportation sector – with a special focus on advanced liquid biofuels. The study is made on assignment of the Norwegian environment agency.

The overview is based partly on statistics of historical and current global biofuel production in general, partly on a thorough mapping of existing and planned production plants that may be able to contribute to advanced liquid biofuel production in the period from now until the year 2030.

With the purpose above in mind, the scope of the study can be further clarified in the following way:

- Main focus has been put at commercial and/or relatively large-scale plants, since these will be the ones that have the potential to substantially contribute to global production. With this said, information about demo and pilot plants has been used to assess the viability of published plans and data. Data are also included in the appendices.
- The basic structure used for the categorization of plants are division between different types of value chains. These are primarily linked to the type of technology used for conversion of raw material into product.
- For assessment of future production, the intention has been to include plants and plant developments that have the *potential* to contribute to advanced, liquid biofuel production. This means for instance that plants are included that currently use conventional raw material if their value chain allows the shift to other raw material.
- Production of biobased gases are only included when there are explicit plans for conversion into liquid fuels.
- Biogas production from anaerobic digestion is – as a value chain primarily including smaller scale plants servicing more local/regional energy markets – not included.
- So called electro-fuels and fuels from waste streams that are not bio-based are not included in this report.

1.2 THE REPORT

In this report, Chapter 2 provides a historical overview of global biofuel production. This is based on published statistical sources or from international renewable energy organizations and includes thus both conventional and, in smaller amounts, advanced biofuels. In Chapter 3, the concept of value chains and the linkages between technological value chains and advanced biofuels, as defined in this report, is described and discussed. These linkages are not clear-cut and need to be understood in order to interpret the data in Chapters 4 and 5 in a meaningful way.

Chapters 4 and 5 include the main results of the study, namely the global production of advanced biofuels. Chapter 4 describes the plant inventory for production of advanced biofuel, partly in relation to existing and operational plants (in the years 2016/2017), partly in relation to plans for investments in additional capacity. In Chapter 5, the result of the assessment of total current and potential production in 2030 is presented. The assessment is based on the plant inventory, but a comparison with modelling results from literature is included.

1.3 DEFINITIONS

In this report the following definitions have been used:

Biofuels – Fuels for use in the transportation sector primarily based on bio-based feedstock, here mostly referring to liquid biofuels, due to the scope of the study.

Advanced biofuels – Biofuels produced from lignocellulosic feedstocks (i.e. agricultural and forestry residues), non-food crops (i.e. grasses, miscanthus, algae) or industrial waste and residue streams, which also are associated with high GHG reductions and that are assumed to be able to reach zero or low iLUC impact.[1]

Conventional biofuels – Biofuels produced from crop feedstocks that may also be used for food or from other feedstocks, but with low GHG reductions or estimated high iLUC impact.

Novel advanced biofuel conversion technologies – Conversion technologies for the production of advanced biofuels, which are not currently commercial and require further technological development.

Commercial biofuel conversion technologies – Conversion technologies that are broadly applied commercially on large-scale, in general producing conventional biofuels but potentially also advanced biofuels, e.g. from waste feedstock.

Value chain – A description of the entire production chain from raw material, via conversion technologies to final biofuel product. A technology value chain is primarily defined based on the conversion technology used.

Large-scale production plant – Plants that are estimated to have a potential to contribute significantly to total advanced biofuel production. In general, partly those plants that are defined as commercial in various databases, and plants larger than about 50 000 tonnes of production are included.[2] These plants are included in Appendix B and in the estimates of global production capacities/potential. The reason for introducing this definition is that some quite large plants are still defined as demonstration plants and vice versa, depending on the type of financing and to technological challenges that are addressed.

Demonstration and pilot plants – Smaller-scale production plants with the main purpose of contributing to technological development.

In addition to these definitions a number of abbreviations have been used. These are, however, defined and, when needed, explained on first occurrence in the report.

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[1] This is the definition used in the EC reports [1], referring to the EIBI, and a very similar definition is used by the IEA [2, 3]. IEA also defines novel advanced biofuels as fuels that meet the advanced biofuel definition, but are not currently commercialized.

[2] The exact limit may differ between type of plant, and depending on other, more qualitative, aspects.

2 GLOBAL PRODUCTION OF BIOFUELS

2.1 DATA COLLECTION

For this report, data on current global production of biofuels for transportation have been based on official statistics for different geographical regions and on compiled data in literature. As part of compiling the results presented below, a number sources have been studied [see 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13]. However, primarily the following sources have been considered to be most complete and consistent and have therefore been used:

- EIA, U.S. Energy Information Administration [4]
- EBB, European Biodiesel Board [5]
- REN21, Renewables 2018 Global status Report [6]
- USDA; Unites States Department of Agriculture, EU Biofuels Annual 2018 [7]

In general, published data on biofuels often use different definitions and units, and the detailed assumptions used are not always clear. As a result, data from different sources seldom fully agree and the differences are difficult to reconcile. Especially, it should be noted that biofuels included in the category "biodiesel" differ, and may include only conventional biodiesel of FAME (fatty acid methyl esters) or both FAME and HVO (hytrotreated vegetable oil) types. The calculations of total energy content of the produced biofuels have been based on sources which specify the quantities in litres or ton in combination with the lower heating values from GREET [14]. The regions and countries specified always refer to the location of the *production* of the biofuels, and not where the volumes are finally utilized.

2.2 TOTAL GLOBAL PRODUCTION OF BIOFUELS – HISTORICAL OVERVIEW

Historically, production of biofuels for use in the transportation sector started to develop in the early twenty-hundreds. Firstly, production of ethanol reached volumes that were visible on a global scale and from about 2005 the volumes of both ethanol and biodiesel production increased strongly.

Total biofuel production is still very small in relation to total use of transportation fuel. In 2017 it was just was about 3.4 % on a global level [3]. The development of biofuel production volumes experienced a dip between 2010 and 2012, but has since increased again. The primary reasons for this development can be found in the development of oil price, which slumped during the economic crisis in 2008/2009, and on policy and market developments in the main markets of Europe, US and Brazil. In Europe, a discussion arose about the sustainability of biofuels, which lead to changes in regulation that both impacted the economic viability of existing biodiesel production and the level of uncertainty for new investments.

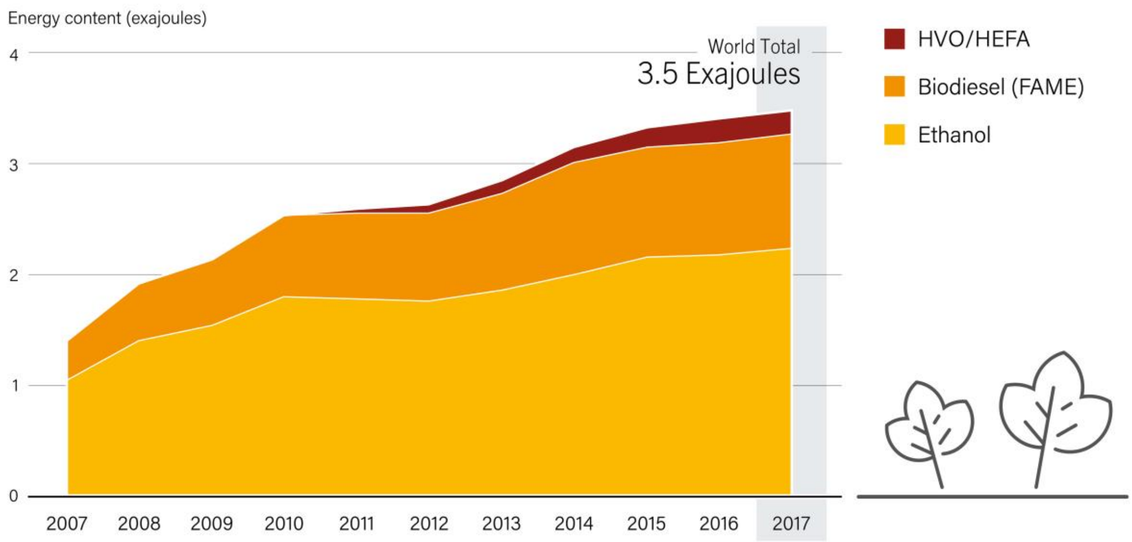

Figure 1 Global production of biofuels – development from 2007 to 2017, from REN21 Renewables 2018 [6]. The 3.5 EJ correspond to 970 TWh, of which 623 ethanol, 284 conventional biodiesel and 61 TWh HVO (about 105, 31 and 6.5 Mm^3, respectively).

As is clear from Figure 1, existing production of biofuels consists almost entirely of ethanol and biodiesel. The production of these two fuels are therefore described in more detail below. The vast majority of biofuel production takes place in so called conventional biofuel plants and is based on raw materials such as sugar cane, corn, wheat and other cereals. Advanced production of ethanol is included in total ethanol production but represents only about 0.1% of total etanol volumes. The production of HVO started to develop around 2010 and is visible in the diagram from 2011. Since then production has continuously been increasing and in 2017, 18 % of the produced biodiesel was HVO, corresponding to about 60 000 GWh.[3]

The Renewables 21 network is the only source of data on historical development of global biofuel production that explicitly include the production of HVO, separate from conventional biodiesel production (see Figure 1). However, when comparing different sources it should be pointed out that this source provides a slightly higher total estimate of biofuel production than other sources. The total amount of 3.5 EJ in 2017 corresponds to 970 TWh/year, while the IEA in its renewables report [3] states that the production was about 920 TWh (3.3 EJ). According to EIA [4], used as source for diagrams in Figures 3 and 5, total global biofuel production in 2016 was only slightly above 900 TWh (see also Appendix A).

Upgraded biogas from anaerobic digestion used for transportation, although having a large potential, is currently very limited. It is in general not included in global data on biofuels production, but hidden in data on natural gas use. Biogas for transportation represents relevant volumes in a few countries, like Sweden and Norway, but total amounts would hardly not be visible on a global scale. Europe represents currently the major market and, there, a total of about 17 TWh of biogas was produced in 500 plants for anaerobic digestion in 2016 [3]. Only a

[3] Roughly two-thirds of this can be classified as advanced biodiesel production, including HVO from PFAD (see also Section 5.2).

smaller share of this was, however, upgraded and used for transportation. Globally, only 1 % of total biogas production was used for transportation [3].

Total biofuel production is dominated by a few countries and regions: As illustrated in Figure 2, two-thirds of all biofuels are produced in Brazil and the US, only. If adding the six following largest producing countries, these eight countries together represents 87 % of global production.

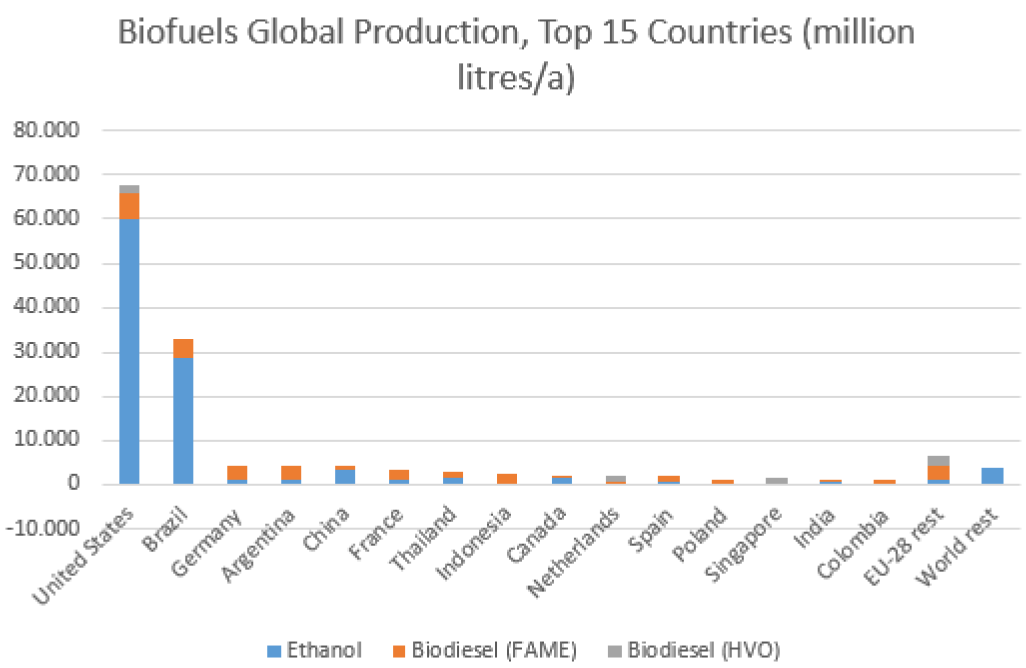

Figure 2 Global production of biofuels 2017, top 15 countries. See also Appendix A for data [6]. This figure is available in units GWh/a in Appendix D.

2.3 GLOBAL PRODUCTION OF ETHANOL

84 % of global ethanol for use as biofuel is produced in Brazil and the US (see Figure 3). In Brazil, the raw material used is sugar cane. Sugar cane based ethanol is a land use efficient biofuel, partly since total biomass and energy content of the crop per hectare is high, partly because of high conversion efficiency from crop to ethanol.[4] As a result sugar cane-based ethanol has also low GHG-emissions compared to the GHG emissions from fossil fuels. Reported reductions in the RED system lie in the range of 75%-80 % [16]. There may still be issues related to social sustainability, working conditions, and on land use.[5] Brazilian producers are also active in development of advanced ethanol production, primarily based on waste

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[4] According to Börjesson et al [17], ethanol from sugar cane can produce almost 170 MJ biofuel/hectare, comparted to about 105 MJ/hectare for ethanol from corn and slightly below 70 MJ/hectare from wheat.

[5] Sugar cane plantations in Brazil are primarily situated in south-east and central-west Brazil, far from rainforests in the north, which limit negative direct land use change. Indirect land use change (iLUC) may still take place, but is not directly linked to where the growth of biofuel crops is located, but rather on the global market situation [18].

streams (sugar cane straw, bagasse) from conventional production and mostly integrated with these plants (see also Chapter 4).

In the US, ethanol is primarily produced from corn. GHG reduction for American ethanol has in general been considerably lower than for that based on sugarcane, because of more fossil fuel intense cultivation and production, together with less efficient production plants. However, there have been strong developments over the last few years of both conventional and advanced ethanol production thanks to increased focus on sustainability issues and, as a result of this, policy changes, such as California's Low Carbon Fuel Standard [3].

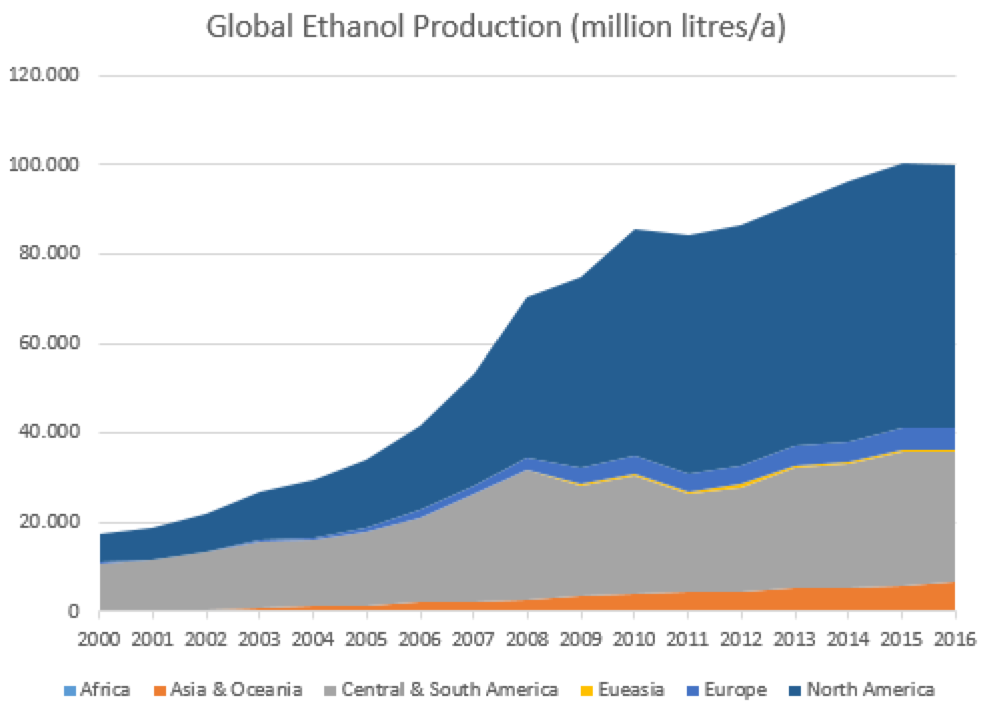

Figure 3 Global ethanol production divided between producing regions (97 % of ethanol produced in Central & South America is produced in Brazil and 92 % of North American production takes place in the US). [4] This figure is available in GWh/a in Appendix D.

In Europe, with a total ethanol production of 4.8 Mm^3, or 5 % of global production, the raw material used varies, but is primarily based on starch crops (e.g. wheat) and to some extent sugar beets. France and Germany are the largest producers, with 0.98 and 0.93 Mm^3, respectively, in 2016 (see Figure 4 and Appendix A). The production in France and Germany has been stagnating over the last few years, while the strongest increase can be seen in the UK and Hungary. It should be noted that most of the "rest" of Europe in Figure 4 consists of Nordic ethanol production. Total production in Sweden in 2016 was about 0.24 Mm^3 (the largest producer being Agroetanol in Norrköping) [20].

The GHG reduction for corn and wheat based production has increased and lies between 58 and 69 % (2017) according to Swedish sustainability reporting [16], and about the same in Germany (2016) [2], both using the RED methodology. The highest reduction is reported for ethanol from food waste, with a CO_2 reduction of 120 %, which is achieved through a combination of waste feedstock and recycling of carbon dioxide [16]. This is an example of continuous developments and improvements of commercial ethanol technologies, leading to improved sustainability, which is further discussed in Section 3.3.

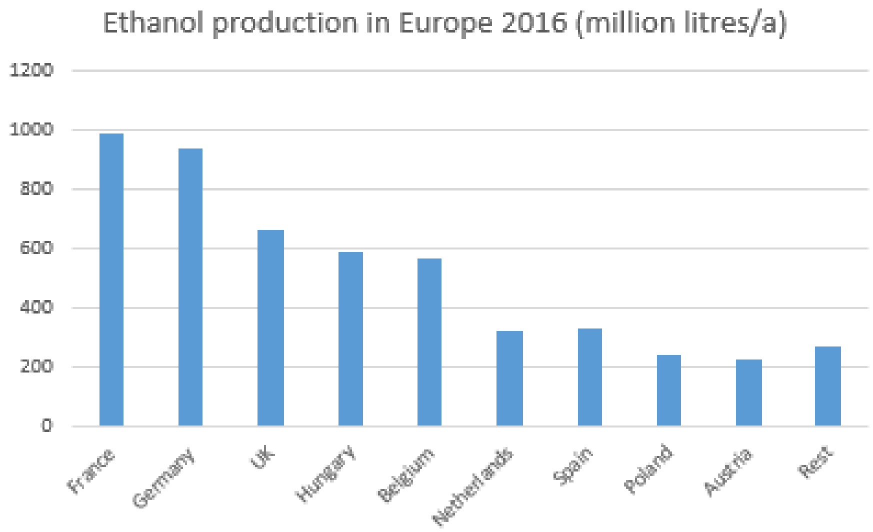

Figure 4 European ethanol production specified between countries [7] See also Appendix A for data. This figure is available in GWh/a in Appendix D.

2.4 GLOBAL PRODUCTION OF BIODIESEL

Global biodiesel production is more evenly spread over the continents, compared with ethanol production (see Figure 5). Total production include both FAME and HVO, of which FAME dominates with about 72 % in 2017, while the production of HVO is increasing much faster.[6] Total production increased strongly until 2015, when a clear dip was experienced. This is probably primarily linked to a similar dip in oil price at the same time. In Europe, the biodiesel market has, however, also been strongly influenced by the prolonged discussion about regulation of iLUC effects and the limit on food-based feedstock. Information about current production of HVO can also be found in Section 4.2 on advanced biofuel production.

The largest production region is in this case Europe, with South America, Asia and North America following. Important producing countries outside of Europe are the US, Brazil, Argentine and Indonesia, which together more or less equalize the EU production. In Europe, the largest producer countries are Germany, France and the Netherlands. In Germany and France production consist of smaller-scale FAME production, while in the Netherlands the majority of the biodiesel production takes place in the Neste large-scale HVO plant.

Production of FAME can be based on different vegetable oils. The choice of raw material is based partly on local growing conditions, market and policy situation and the quality requirements of the final products, since, for FAME, the quality of the biodiesel is linked to

[6] The sources used for the diagrams in this section do not specify HVO production, separately, or specifically note that HVO is included in total biodiesel production. However, from data for specific countries (e.g. Finland) we can draw the conclusion that HVO are included in total numbers.

which oil is used as raw material.[7] In the Nordic countries, FAME biodiesel produced (and used) consists primarily of RME, since rapeseed oil gives the best properties for a cold climate.

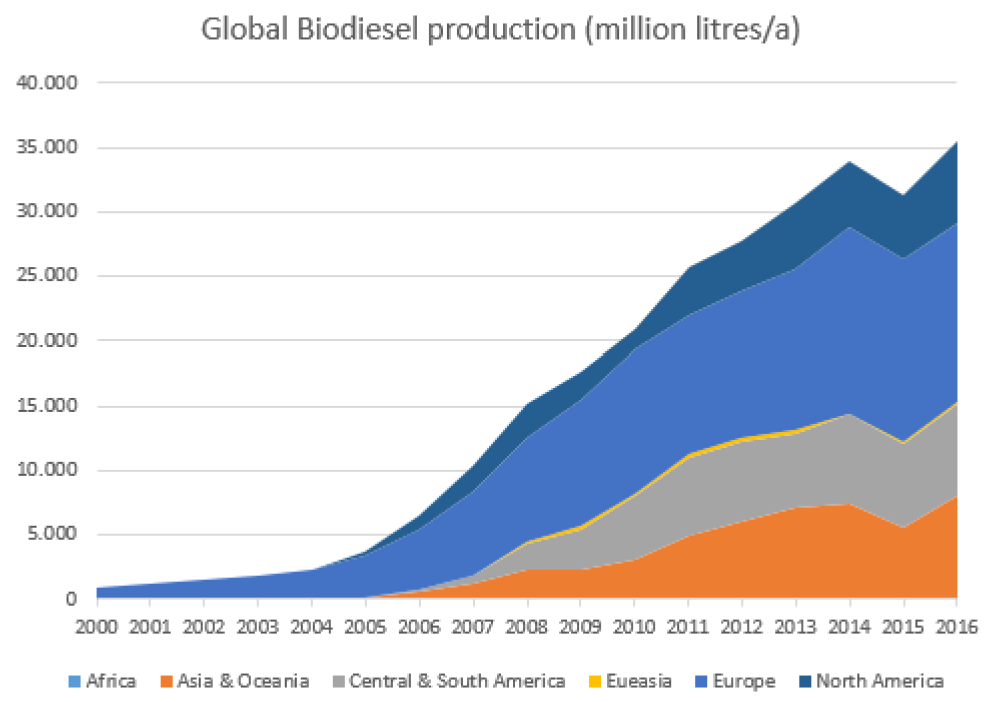

Figure 5 Global biodiesel production divided between producing regions. [4] This figure is available in GWh/a in Appendix D.

GHG reduction data for FAME are typically lower than for ethanol, but vary substantially and have been gradually improving. Reported GHG reduction for the RME used in Sweden was in 2017 about 60 %, which was an increase from below 40 % (close to the EU default value) in 2011 [16]. In Germany reported data for biodiesel increased from about 55 % in 2014 to above 70 % in 2016 (however, it is not clear whether this reflects a shift to HVO or waste oils for feedstock) [2]. One reason for these, comparably, low numbers are that the yield from raw material to biofuel (FAME) is lower for this value chain, while the share of co-products (used for animal feed) are larger. Other reasons are that cultivation of oil crops is energy intense and that the process also requires methanol, which in general is fossil fuel based. An example of improvements and developments is thus the use of renewable methanol in the Perstorp production plant in Sweden.

GHG reduction data for HVO production vary, depending on feedstock used. Examples of data from the Swedish biofuel sustainability reporting shows values such as 60 % for rape seed oil, about 68 % for palm oil and between 80 and 90 % for waste based oils (tall oil, animal residue fat, and waste corn oil, PFAD). In these data, no estimates of emissions arising from iLUC are included.

[7] FAME is the general name, while other abbreviations are used depending on raw material, e.g. RME for Rape Methyl Ester and PME for Palm oil Methyl Ester.

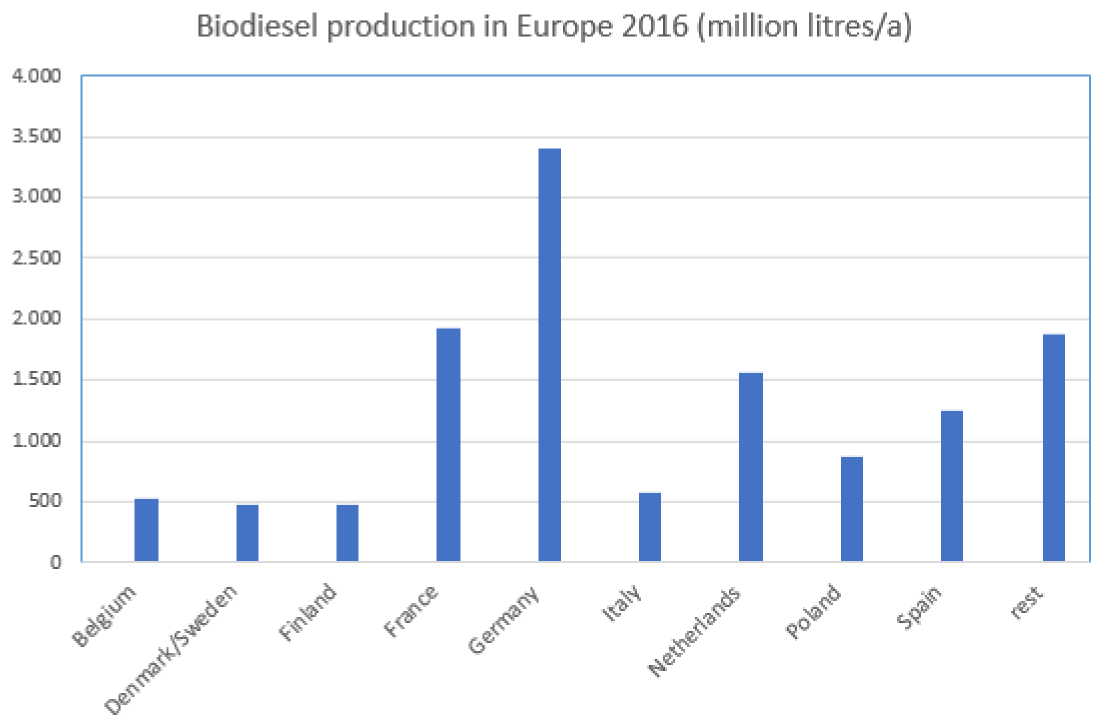

Figure 6 European biodiesel production divided between main producing countries. [5] This figure is available in GWh/a in Appendix D.

3 VALUE CHAINS FOR PRODUCTION OF ADVANCED BIOFUELS

3.1 THE CONCEPT OF TECHNOLOGY VALUE CHAINS FOR ADVANCED BIOFUEL PRODUCTION

Technology value chains, or conversion pathways, for advanced biofuel production are used to describe the entire production chain from raw material, via conversion technologies to final biofuel product. The term technology value chain is here used to stress that in this report the value chains used are primarily based on the conversion technology used, and the potential raw materials and products are treated as a result of the properties, limitations and flexibility of this technology.

Value chains for the production of advanced biofuel production, according to the definitions used in this study, may include both commercial and novel conversion technologies.

As part of the work carried out by European Industrial Biofuel Initiative (EIBI) and European Biofuels Technology Platform (EBTP) seven distinctive bioenergy value chains were identified, that have since been generally adopted and used e.g. in the reports from the Sub Group on Advanced Biofuels within the Sustainable Transport Forum (SGAB).[8] Six of these value chains are relevant to the production of advanced biofuels (see Figure 7 and Appendix B). For a detailed and up-to-date description of the technologies included in these value chains and their technological status and reliability, we refer to the SGAB technology report [19, 23].

These value chains were thus developed before the fast growth of HVO production. Further, at this point in time, electro fuels were not on the agenda while fuel production from algae were (very much so). As a result, the original value chains are not completely up-to-date. A review of the value chains has been discussed (within the current European Technology and Innovation Platform, ETIP Bioenergy), but not yet finalized. Here, we therefore use the EIBI value chains, complemented with information on other value chains from for instance the ETIP Bioenergy web page and the SGAB report [19, 23].

Thermochemical conversion of biomass into biofuels are in the EIBI value chains divided into three different chains: VC1 – production of liquid transport fuels via gasification; VC2 – production of bio-methane via gasification; and VC4 – production of intermediate bioenergy carriers for upgrading into transport fuels via other thermochemical processes.[9] In the SGAB report these value chains have then been complemented with a value chain for the production of HVO. In the SGAB report this was included in the group of thermochemical conversion, below and in Appendix A we describe it as oleochemical conversion.

Biochemical conversion of biomass into biofuels are in the EIBI value chains divided into two different chains: VC5 – production of ethanol and higher alcohols via fermentation; and VC6 -

[8] The Sustainable Transport Forum was an initiative during 2016-2017 by the DG Transport of the European Commission, bringing industry together to explore the development of sustainable transportation within the EU. The sub-group on advanced biofuels produced three reports: the final report, a technology report and one cost-of-biofuels report.
[9] VC4 includes also production of intermediate bioenergy carriers for other purposes (heat and electricity production), but these are outside the scope of this study.

production of renewable hydrocarbons (liquid drop-in transport fuels) via biological or chemical processes (including fermentation). These two value chains were in the SGAB report also complemented by the value chain of anaerobic digestion for production of compressed or liquid bio-methane for transportation (not included in this study).

The final EIBI biofuel value chain VC7 – production of transport fuels from algae, via various conversion technologies, differs from the other EIBI value chains in that it is not based on type of conversion technology, but on the origin of the raw material. Aquatic biomass can in principal be used as raw material in most of the value chains described above, depending on the type of aquatic biomass in question and the amount and type of pre-processing introduced. As a result the flexibility for VC7 on the product side is large.

Finally, in the SGAB report these value chains have also been complemented with value chains for so called electro-fuels.

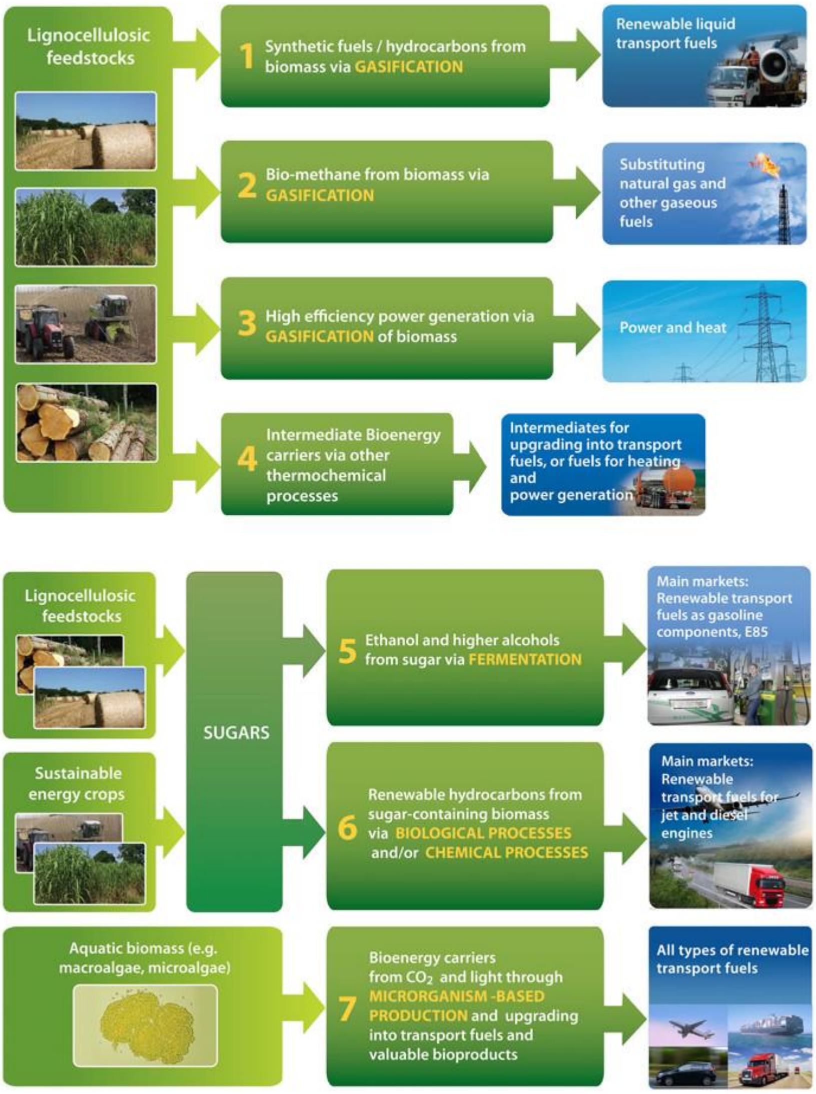

Figure 7 The seven EIBI bioenergy value chains [19]. For complete flow charts and descriptions, see Appendix B.

3.2 VALUE CHAINS USED IN THIS REPORT

Based on the purpose and scope of this study, we are here focusing on the value chains that are likely to contribute to the production of *liquid* biofuels in relevant volumes during the time period from now until 2030. Data on existing and planned production plants have therefore been divided in the following way:

Gasification for the production of liquid biofuels

> The plants included here consist primarily of high-temperature gasification and syngas upgrading, described by EIBI VC1. There are technologies also for converting biomethane from gasification (VC2) into liquid fuels, and such plans are in principle included (but scarce).

Fermentation for the production of alcohols (primarily ethanol)

> The plants included here are primarily included in VC5, using fermentation based on both variants of traditional yeasts and engineered yeasts. Existing plants use primarily crop residues and waste, while planned plants also include wood based feedstock. There are currently no plans for larger-scale plants based on other types of biological or chemical processes (VC6) for the production of hydrocarbons, although development is ongoing (see also Section 4.3.2).

Hydrotreatment of fatty acids for the production of HVO

> The plants of this value chain include partly HVO production based directly on waste and residue fatty oil and greases (FOG), partly production plants that include more challenging preprocessing steps (of the type included in the next group of plants) of other feedstocks. Further, it includes both stand-alone plants, plants integrated with refineries and co-processing plants.

Thermochemical conversion for the production of intermediate bioenergy carriers

> The plants included here use primarily different types of pyrolysis processes, with or without catalysts, and in some cases other types of liquefaction technologies. The plants included are mostly smaller-scale plants that are intended to deliver their products to hydrotreatment plants or for gasification. Thus, the capacity of these plants are *not* additional to the other ones, but increases the potential of supplying the plants above with sustainable biomass.

There are no plans for large-scale plants to produce biofuels based on algae as raw material (VC7), therefore no such value chain is included. Further, production of bio-methane via anaerobic digestion (biogas) is not included. Bio-methane from anaerobic digestion of for instance sewage sludge, manure and other biological waste is a mature value chain with a large global potential. However, here it is expected that production plants remain smaller-scale and therefore not likely to be linked to further (larger-scale) conversion into liquid fuels. Electro-fuels and other synthetic fuels are outside the scope of this study.

3.3 RELEVANCE OF SYSTEM LINKAGES AND TECHNOLOGY FLEXIBILITY

Different technology value chains have different system linkages and different levels of flexibility in terms of raw material base and potential end products. This means for instance that one plant may, with more or less difficulty, be converted from one feedstock to another. This is especially important to be aware of when basing the definition of *advanced* biofuel on the type of feedstock used. Below, some related aspects especially relevant for this study are noted.

Embedded level of flexibility depending on type of conversion

Generalized, value chains for conventional biofuel production are more adapted to a certain type of raw material and a certain end product than those for advanced biofuel production.

For instance, commercial fermentation into alcohols is dependent on sugar (or starch) rich raw materials and produces ethanol. This can be explained by the basic chemistry behind technology development and the processes – fermenting sugar into alcohol is a process that takes place in nature and the development into an industrial process has been comparably straightforward. When we strive to use more complex raw materials, we need to develop new and gradually more advanced technologies, such as engineered and adapted yeast strains, and these developments open also for alternative products, such as higher alcohols. More complex raw materials also increase the demand on pretreatment prior to the biochemical conversion process, making sugar fractions accessible for the yeast strain.

Another important aspect is the fact that the more one needs to break up the molecular structure of the raw material for a given technology value chain, the more process steps need to be added to synthesize the products back into liquid fuel and, as a consequence, the flexibility of final biofuel product increases. The most extreme example is the gasification of "any" cellulosic material into the basic molecules of H_2 and CO (syngas), which then can, in principle, be synthesized into any desired fuel – for instance fishcer-tropsch-diesel (FT-diesel) or jet fuel. On the down side of such conversion routes are more complex processing steps, potentially higher energy loss and higher technology costs.

Waste and residues as feedstock for advanced biofuels

The definition of advanced biofuels used for this study, and elsewhere, is primarily based on the type of feedstock used, where all types of feedstock based on waste and residues are considered advanced (with high sustainability values). This means that advanced biofuels may very well be produced in plants for commercial conversion. There are substantial amounts of waste and residues that have a chemical structure similar to feedstock that *can* be used for food. Examples include the use of waste bread for production of ethanol in the St1 Ethanolix plants and by Lantmännen (in Sweden). Similarly, technologies "in-between" commercial and novel technologies are developed in order to utilize a larger share of the conventional raw material. The regulatory (in the US) and technological development that has made it possible to ferment corn kernel fibre in conventional corn ethanol plants is one such example (see Section 4.2.2).[10]

[10] These developments are sometimes called 1.5 generation biofuel production.

Increased utilization of waste for higher-value products leads to improvements in total resource efficiency and overall sustainability. However, the sustainability criteria used in for instance the EU (RED and RED II), where the emissions accredited to feedstock classified as waste and residues are zero, also lead to an increasing demand for (and value of) waste material. This may create a skewed market situation, conflicts with measures aiming at minimizing waste flows, and less focus on technological development needed for large-scale and long-term sustainable fuel production.

Competition for feedstocks between different types of advanced biofuel production

The production of sustainable biofuels contributes to decreasing GHG emissions, by competing with and substituting for fossil fuels. However, there is also competition between biofuels, which may impact the deployment of different value chains.[11] To achieve system benefits from utilizing existing infrastructure, there is a push towards biofuels that have the same properties as fossil fuels currently used, such as drop-in diesel fuel and biojets. This drives the development towards more flexible value chains, partly through technologies such as gasification, but may also result in the addition of process steps to the value chains for production of e.g. ethanol in order to produce more complex hydrocarbon fuels. This is also an important aspect behind the development towards increasing involvement of traditionally fossil refinery companies in biofuel production and the developments to increase the feedstock alternatives for oleochemical conversion (see below). A result of these above trends is that different value chains increasingly compete for the same type of (lignocellulosic and waste based) feedstock.

For the purposes of this report, focusing on the availability of liquid biofuels for the Norwegian market, also the potential competition between feedstocks for liquid and gaseous fuels (primarily bio-methane) is of interest. The development of bio-methane production based on gasification does directly compete with the same feedstock as most value chains for liquid biofuels. For bio-methane production via anaerobic digestion, however, the question is more complex. This value chain has a large potential, is (more or less) commercial, mainly based on waste and residues for feedstock and sustainably contributes to the local systems of waste handling and energy supply. Competition between feedstocks used for biogas production and liquid fuels is primarily relevant for sorted food wastes, such as waste sugar and starch rich products (bread, cereals, sweets) and waste streams in commercial biofuel plants, that may increasingly be used for ethanol production, and concentrated fractions of fatty residues, that may be a suitable feedstock for HVO production.

Biogas production based on wet and mixed substrates – e.g. waste water and sewage streams, manure and mixed biological household waste - would not be subject to competition in the same way. The conversion efficiency from substrate to biofuel is higher and the technology less complex, which leads to economic advantages of anaerobic digestion for these feedstocks, as well as larger GHG reductions. Further, these substrates are more costly to transport, which favors more local and small-scale solutions, such as anaerobic digestion. With technological

[11] In addition, there is competition with the use of biomass for other biobased products and for the conversion into other renewable energy carriers (electricity and heat). Overall biomass utilization is studied in many system analyses, but not further discussed here.

development, the competition may increase in some specific cases, e.g. the pretreatment method of hydrothermal liquefaction is discussed for sewage sludge.

These technological development trends that are impacted by policy and the biofuel and vehicle markets, do not necessarily increase the total potential for sustainable biofuels, but impact the type of plants that are being built.

The development of HVO production in integration with fossil refineries

Over the last few years we have seen a strong increase in bio-based HVO production by large, mostly international, industrial actors with a basis in the fossil refinery sector and, in the Nordic countries, forest industry. As can be seen in Chapters 4 and 5 of this report, according to available plans for plant developments this is a trend that seems to be continuing. The realization of these HVO plants will thus have a major influence on total amounts of advanced biofuel on the global market. However, HVO production in the same facilities can be both conventional and advanced (according to the definitions used here), depending on the type of feedstock used. Only part of the HVO production today can be classified as advanced biofuel and the potential for fatty waste and residues that can be used for HVO without novel technology developments is limited (see also Chapter 5). Therefore, the provision of sustainable feedstocks and technological developments to expand the feedstock range need to be considered in particular when evaluating this development.

The focus on HVO as drop-in diesel fuel has been especially strong in the Nordic countries, partly due to the early use of talloil from the forest industry as feedstock having positive sustainability performance and, as a result, favorable regulatory frameworks. Therefore, a substantial share of global HVO production is currently used in Sweden and Finland. The knowledge about HVO as an advanced biofuel and the view on its future role for sustainable transportation differ therefore internationally.

It should be noted that current HVO production is not always included in data on advanced biofuels in literature, even when the same definition is used as for this study (see also Section 5.3). This is partly due to its mixed use of feedstock, including both waste materials and virgin vegetable oils, but also because of the value chain's close integration with fossil refineries as such, which is controversial in some contexts.

Finally, based on the same logic, the production of FAME through esterification, may – depending on the feedstock used - be a value chain relevant for advanced biofuel production as well. As for HVO production, the feedstock may be partly waste-based, producing partly advanced biofuels. The advanced share may increase further, by using bio-methanol in the production process.

4 GLOBAL PRODUCTION OF ADVANCED LIQUID BIOFUELS

4.1 DATA COLLECTION

The data presented below are based on plant and company specific information which has been compiled from a range of sources. Databases covering advanced biofuel (and biochemical) production plants are compiled and managed by IEA tasks 33, 34 and 39 [22]. These have been used as a basis for the data collection, both for identifying production plants and for obtaining data relating to the identified plants. The information included in these databases has then been cross-checked with other sources and complemented through information obtained in literature and on current conferences. Some of the most important complementary sources are the following:

- Technology status report compiled by the European commission's sub group on advanced biofuels (SGAB) [23]
- Bioenergitidningen's 2018 review of advanced biofuel plants in the Nordic countries [24]
- Greenea 2016 report on global HVO production status [25]
- US national renewable energy laboratory (NREL) 2016 report on bioenergy status [26]
- E4tech 2017 report on cellulosic ethanol plants [27]
- US department of energy report on renewable aviation fuels [28]
- Press releases, annual financial/sustainability reports and similar
- Presentations held at the 2018 Advanced biofuels conference in Gothenburg, Sweden [29-35].

Finally, data for some of the plants and companies have been double-checked and updated after direct contacts with other experts in the field as well as, in a few cases, company representatives.

For each value chain plants are included that are estimated to potentially contribute to the production of advanced biofuels over the next 5-10 years. They are divided into three groups: 1) existing and operational plants, 2) existing and idle plants, and 3) planned plants ordered roughly after the year of planned start-up.

In the tables, data on plant location, technology, company and existing or planned production capacity can generally be considered fairly certain. On the contrary, data on start-up year, actual yearly production of biofuels and all types of economic data are most often uncertain. Information about the latter two types of data is in most cases difficult to obtain, at least officially and "referenced". For many plants, generalized economic data have therefore been included instead, mostly based on the SGAB report [36], which is considered the most recent and reliable source available.

Geographically, data relating to the Nordic countries, within the EU and the US are generally more detailed and verified by several sources and, consequently, considered more reliable. The level of uncertainty is higher for plants located or planned to be built in Asia (mainly in China). We have not made any attempts to control data for these plants through direct contacts.

Appendix C contains data for all plants identified, including information about data sources.

4.2 EXISTING AND OPERATIONAL PLANTS AND PRODUCTION

4.2.1 Plants based on the value chain for gasification

There is currently only one plant that produces liquid biofuels based on gasification of advanced biomass (VC1), globally. This is the Enerkem plant in Edmonton, Canada, with a nameplate capacity of about 38 000 m^3 ethanol per year. This plant was initially constructed for methanol production, with an ethanol conversion unit added in 2017 [22, 37]. As of February 2018, the plant had not yet reached nameplate capacity [38].

Table 1 Existing and operational gasification plants for production of liquid biofuels. For complete references for data in this table, see the corresponding Table C1 in Appendix C.

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
Enerkem Edmonton (Canada)	Operational	MSW	Ethanol (methanol)	225 (38 020)

Gasification plants where the end product is not a liquid fuel may produce e.g. syngas for production of heat and power or chemicals. Such plants do exist, but have not been included in this study. Further, a methanation unit may be added for conversion of syngas to biomethane for the transportation market. This was for instance the case in south-west of Sweden, where a strong regional focus on bio-methane from anaerobic digestion, the existence of a natural gas grid and the interest in bio-based SNG as raw material for the chemical industry led to plans for the E.ON B2G plant and the GoBiGas plant in Gothenburg. Due to low fossil fuel prices, the plans for large-scale gasification based bio-SNG plants have been put on hold and the first-of-a-kind plant GoBiGas, phase 1, in Gothenburg, Sweden is being moth-balled. There are currently no commercial scale plants operating using this technology. [21]

4.2.2 Plants based on the value chain for fermentation into alcohols

The development of fermentation of cellulosic material for the production of ethanol lead to commercialization and the construction of all-in-all about 11 such plants between 2009 and 2016. However, after 2014 the market slumped, primarily due to a combination of decreasing oil price and regulatory uncertainty. As a result, one third (4) of the built plants have since been idled for economic reasons [22, 39, 40, 41]. Data on annual production is scarce for the still operational plants, but available data indicates that nameplate capacities are far from reached (see Appendix C).

In general, the plants built, including of course all those still operational, are based on by-products and waste from conventional production of ethanol – corn stover/cobs, bagasse, other agricultural residues - and, to varying extent, integrated with the conventional production plants. This also means that the value chain for all existing and operational plants can be described as fermentation for the production of ethanol as blend-ins for the gasoline market or E85 (VC5).

In addition to the recently constructed cellulosic ethanol plants, two older plants, ChemCell Ethanol in Norway [42, 43] and Domsjö fabriker in Sweden [44], integrate ethanol production with the sulphite pulping process. Both plants have produced ethanol for several decades, and production at Domsjö fabriker exceeded nameplate capacity in 2017 [45]. Production data for the ChemCell Ethanol plant is unavailable but capacity utilisation is likely to be high. Note that these plants produce ethanol as a by-product, and that sulphite mills represent only a few percentages of total chemical pulping capacity, meaning development along this path is limited.

Table 2 Existing and operational advanced plants for fermentation of cellulosic material into bio-ethanol. Grey rows include more general, not plant specific, data. For complete references for data in this table, see the corresponding Table C2 in Appendix C.

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
ChemCell Ethanol (Norway)	Operational	Sulphite liquor	Ethanol	118 (20 000)
Domsjö fabriker (Sweden)	Operational	Sulphite liquor	Ethanol	105 (17 740)
Project Liberty, Poet-DSM (US)	Operational	Corn-stover	Ethanol	558 (94 500)
GranBio Bioflex 1 (Brasil)	Operational	Sugar cane bagasse and straw	Ethanol	472 (80 000)
Raizen Energia (Brasil)	Operational	Bagasse	Ethanol	249 (42 200)
Cane Technology Center (Brasil)	Operational	Bagasse	Ethanol	18 (3 040)
Longlive biotech (China)	Operational	Corn cob	Ethanol	446 (75 600)
Henan Zhenping (China)	Operational	Wheat/corn stover	Ethanol	75 (12 670)
Henan Nanyang (China)	Operational	Crop residues	Ethanol	225 (38 020)
Aggregated in conv plants[1] - USA	Operational	Corn kernel fibre	Ethanol	690 (116 800)
Aggregated in conv plants[1] - Nordic	Operational	Food waste	Ethanol	About 150 GWh[2]

[1] Production of advanced ethanol from waste material, in mainly conventional ethanol plants.
[2] This estimate is only included to give an order of magnitude, data is uncertain.

In the US, corn kernel fibre is considered cellulosic feedstock since 2014. The fibre is not accessible by traditional first generation technologies, but the drivers towards increasing efficiency and utilization of waste material have during the last couple of years lead to the development of bolt-on technologies for utilisation of the corn kernel fibre in conventional ethanol plants [26]. In its 2016 report on the bioenergy industry status, the US National Renewable Energy Laboratory (NREL) includes these developments as cellulosic ethanol plants. They are, however, neither listed in the EIA databases [22] nor in the E4tech report [27] on cellulosic ethanol. The aggregated entry in the table above lists the total (US) capacity for cellulosic ethanol production from corn kernel fibre, assuming that all projects listed as either operating or planned in the NREL report are now operating (in total 12 plants).

Similarly, advanced biofuel production based on sugar and starch rich food waste takes place in a number of, otherwise technologically conventional, production plants. In the Nordic countries St1 produces ethanol in, in total, 6 small-scale plants in Sweden (1) and Finland (5) and Lantmännen has integrated production of waste-based ethanol in their conventional ethanol plant in Norrköping. Globally, there may be more developments of this type of advanced ethanol production from waste streams, however no concrete data or information have been found in literature.

4.2.3 Plants based on the value chain for hydrotreatment of fatty acids

The most dramatic development in renewable biofuel production since 2010 has been the evolvement of commercial HVO production. Globally, there are currently about 15 large-scale, commercial plants for the production of HVO (including co-processing with fossil feedstock in traditional refineries), which is used as a renewable drop-in diesel fuel mostly blended in fossil diesel [23, 25]. The global HVO market is dominated by Neste. This company is an advanced biofuels veteran, having operated its first commercial HVO plant since 2007 [23]. The long experience is reflected by a high capacity utilisation, with an aggregated total of 98 % for the company's four plants in 2017 [46]. Neste produces HVO in stand-alone units which produce a diesel quality of HVO. This production strategy, of stand-alone units on refinery sites or complete refinery conversions, is a production strategy shared with most other actors listed in Table 3. Alternatively, HVO can be produced by co-processing of renewable and fossil feedstock in traditional refineries. This strategy is used by the companies Preem, Cepsa and Repsol listed in Table 3 [25].

Industries involved in these developments consist mainly of large refinery companies – in addition to the four refineries already mentioned above, ENI, Total and Sinopec petroleum companies can be included in this group. Additionally, the Diamond Green Diesel plant in US is owned by petroleum refiner Valero via a subsidiary. However, a few exceptions exist: the AltAir and the REG Geismar plants are owned by renewable fuels companies and UPM is a company within the forestry industry, mainly operating pulp and paper mills.

Neste uses a mix of different oils as raw material. It has had a continuously increasing share of waste based feedstock. In 2016, 76 % of total feedstock was waste based, including PFAD, and in 2017 the share was 82 % [46, 77]. Preem and UPM base their production primarily on talloil, being a residual by-product from the forest industry, as feedstock. After Preem's expansion of production capacity in 2015 they have added other waste feedstock, but use, however, no palm oil or PFAD in their production [47].

Table 3 Existing and operational plants for HVO production. For complete references for data in this table, see the corresponding Table C3 in Appendix C.

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
Neste Porvoo 1+2 (Finland)	Operational	Various FOG [1]	HVO	4 870 (509 560)
Neste Singapore (Singapore)	Operational	Various FOG [1]	HVO	13 390 (1 401 270)
Neste Rotterdam (Netherlands)	Operational	Various FOG [1]	HVO	13 390 (1 401 270)
UPM Lappeenranta (Finland)	Operational	Crude tall oil	HVO	1 217 (127 390)
ENI Venice (Italy)	Operational	15 % UCO, 85 % vegetable oils	HVO	3287-4260 (343 950-445 860)
Diamond Green Diesel (USA)	Operational	UCO, animal fats, inedible corn oil [2]	HVO	9 933 (1 039 500)
REG Geismar (USA)	Operational	Crude, high FFA and refined oils and fats [3]	HVO	2 709 (283 500)
Preem Göteborg (Sweden)	Operational	Crude-tall diesel, animal fats, rapeseed oil [4]	HVO (co-processed)	2 102 (220 000)[5]
AltAir (USA)	Operational	Inedible agricultural fats and oils	HVO (jet-quality)	1 445 (151 200)
Cepsa Refineries (Spain)	Operational	FOG	HVO (co-processed)	730 (76 400)
Repsol Refineries (Spain)	Operational	FOG	HVO (co-processed)	730 (76 400)

Sinopec (China)	Operational	FOG	HVO (jet-quality)	243 (25 480)
Total La Mede (France)	Operational[6]	Vegetable oils, used/residual oils, animal fats	HVO	6 086 (636 490)

[1] Aggregated feedstock mix for all Neste HVO-plants is: 76 % waste and residues (including PFAD), 24 % vegetable oils (Neste annual report 2017), increasing to 82 % in 2017.
[2] No food-type feedstock according to company (https://www.diamondgreendiesel.com/what-is-green-diesel)
[3] FFA: Free fatty acids. Company annual report:
http://www.annualreports.com/HostedData/AnnualReportArchive/r/NASDAQ_REGI_2016.pdf
[4] Mainly tall-diesel. No palm oil or PFAD: https://www.preem.se/om-preem/insikt-kunskap/gronare-drivmedel/satsning-pa-fornybar-diesel-ar-viktigare-an-nagonsin/
[5] The production capacity will, by new investments in hydrogen production, increase to 320 000 tonnes in 2019 [104].
[6] Operational since June 2018.

4.3 IDLE AND PLANNED LARGE-SCALE PLANTS

4.3.1 Plants based on the value chain for gasification

There are a limited number of concrete plans for the construction of gasification plants in the near future, probably as a result of limited large-scale experience so far. In total, there are for plans published for seven additional plants (or the production of liquid fuels, most of them with planned start-up in 2019-2020. Enerkem, the company that has developed and is running the plant in Edmonton and thus has hands-on experience, have plans for two more plants. The first is one additional plant in Canada (Varennes) of about the same size as the existing one in 2019 and the next a much larger-scale plant in Rotterdam, Netherlands [22, 48, 49]. The latter is intended for producing methanol to be used in the chemicals industry, but changing market conditions may make fuel production more favorable and the plant has been included in the table below.

In the US, construction work has started on two gasification based plants and completion is expected within the next couple of years [50, 51]. Note that the syncrude produced at the Fulcrum Sierra must be processed further to be suitable as biofuel for transportation (in internal combustion engines) and that the plant, thus, also could have been classified as a plant for production of intermediate bioenergy carriers.

One additional US-plant is planned by the company Aemetis. This plant is based on gasification of biomass followed by syngas fermentation to ethanol using LanzaTech's ethanol technology, and a demonstration plant has been successfully operated [52]. LanzaTech is involved in several similar projects based on fermentation of flue gas streams from e.g. refineries or steel mills. In 2018, their first commercial scale plant was commissioned in China, utilizing steel flue gas as feedstock [35]. Note that the plants based on refinery- or steel mill flue gas are not included in this report. One could also note that this technology (or similar) for producing ethanol from syngas, thus could potentially be used at a wider scale for producing liquid biofuels from biomass gasification plants and technologies now directed towards other markets (see Section 4.2.1). In addition to this plant, there are, however, no other published plans in this direction.[12]

In Table 4, the plan of the Chinese company Kaidi for a very large-scale plant in Finland, for the production of FT-diesel from forest residues, is included. The company has previously operated a pilot in China, but according to contacts with expertise, the completion of the project may be unlikely and at least unrealistic within the published time schedule [104].

One additional FT-diesel plant with the same capacity is planned in France. The project, BioTfueL, is a co-operation between Total Oil, Thyssenkrupp and four additional partners. Demonstration plants were erected in 2017-2018 and tests will be executed for three years. After finishing the test period, a 200 000 t/y plant is planned. Consequently, construction of the planned commercial plant cannot be expected to start until 2020. [23, 53]

Table 4 Planned large-scale gasification plants for the production of liquid biofuels. For complete references for data in this table, see the corresponding Table C4 in Appendix C.

Plant	**Status**	**Feedstock**	**Product**	**Capacity** *GWh/y (m^3/y)*
RedRock Lakeview (USA)	Under construction	Forest residues	Diesel-type fuel	576 (57 000)
Fulcrum Sierra (USA)	Under construction	MSW	Syncrude	421 (36 960)
Enerkem Vanerco (Canada)	Planned - 2021	Mixed waste	Ethanol (methanol)	225 (38 020)
Aemetis/LanzaTech (USA)	Planned - 2019	Biomass	Ethanol	262 (44 360)
Enerkem Rotterdam [1] (Netherlands)	Planned	Mixed waste	Methanol	1228 (277 780)
Kaidi Kemi (Finland)	Planned - 2019	Forest residues	FT-diesel	2403 (239 520)

[12] This technology converts syngas (H_2+CO) into ethanol via microbial conversion. It would also be possible to convert methane, from for instance anaerobic digestion, into liquid biofuels. However, most of the process concepts proposed are based on steam reforming converting methane to syngas and synthesizing liquid fuels such as methanol, gasoline, jet fuels or diesel. These type of plants are often stated to only be economically feasible at large scale. At the relatively small scale of biogas plants, this hardly is feasible without major technology developments simplifying the process design and reducing investment cost. Finally, energy conversion efficiency of methane to diesel-like fuels is in the range of 30%, substantially penalizing the conversion to a liquid fuel from an energy perspective.

BioTfueL commercial (France)	Planned – 2020:s	Various biomass	FT-diesel	2403 (239 520)

[1] The plan for this plant is to produce methanol for use in chemicals production

4.3.2 Plants based on the value chain for fermentation into alcohols

The development of biochemical plants, also when looking towards the (near) future, is more or less entirely focusing on ethanol production from fermentation. Within this group of non-operational biochemical plants there are two sub-groups. The first one consist of already built, but currently idle, plants while the second group consist of plants that are under construction or, most of them, in the planning process.

The group of currently idle plants are in general based on the same type of technology and feedstock as the operational plants described above. After the technological break-through for advanced ethanol fermentation, the market slumped and several of the plants were only up-and-running for a couple of years. Of the idled plants listed in Table 5, Beta Renewables was sold to Versalis (a subsidiary of Italian petroleum company Eni) in 2018 [39], the Hugoton plant has been sold by original owners Abengoa to SynataBio [40] and the DuPont plant has recently been sold to the company Verbio, which apparently will convert it into a biomethane production plant [41, 80]. Further, INEOS Bio seem to have sold its technology to China and plant equipment to other actors [104]. This makes the future of all four plants highly uncertain.

Table 5 Idle large-scale advanced fermentation plants. For complete references for data in this table, see the corresponding Table C5 in Appendix C.

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
Beta Renewables Crescentino (Italy)	Idle	Straw, arundo	Ethanol	299 (50 700)
SynataBio Hugoton [1] (USA)	Idle	Corn stover	Ethanol	558 (94 500)
INEOS Bio (USA)	Idle	Vegetative and wood waste	Ethanol	179 (30 240)
DuPont Nevada (USA)	Idle	Corn stover	Ethanol	670 (113 400)

[1] Previously owned by Abengoa

The majority of the planned plants based on fermentation (the second group) are, in contrast to those above, planned to be more stand-alone from conventional bioethanol production and focusing on cellulosic feedstocks such as “general” agricultural residues, waste and forest residues (wood). Geographically, the planned plants are fairly broadly distributed, including plans for construction primarily in the US, Europe (including the Nordic countries) and China (see Table 6).

A few actors deserve to be mentioned specifically. Clariant is a specialty chemicals company which has developed its own technology for cellulosic ethanol production, and has experience from operating a demo plant in Straubing, Germany [22, 54]. Two large-scale plants based on Clariant's technology are planned in Europe. The construction of the first one, in Romania, was recently initiated (announced September 12, 2018) [54].

BetaRenewables, who also owned one of the existing plants that were operational 2013-2017 also have announced that they have two plants currently under construction in Europe, and plans for an additional one in China. However, since the existing plant in Crescentino is currently idle and Beta Renewables was sold in 2018, the status of all Beta Renewables' projects is highly uncertain.

In China, the Henan Tianguan Group, which already runs two plants, should be mentioned. It plans to build a – for biochemical ethanol plants – very large-scale plant, almost four times the size of their currently largest (and double the size of the largest operational plant in total) [22, 26].

In terms of feedstock, the plant under construction by Fiberight in Hampden (Maine, USA) stands out by utilizing fermentation of municipal solid waste (MSW) for ethanol production. In Fiberight's process, the organic fraction is separated from mixed waste and processed through enzymatic hydrolysis and fermentation to produce ethanol. The company began operating a demonstration plant in 2012 and construction work on the commercial plant started has begun. After several delays, start-up is now planned for 2019. [55, 56]

The 12 plants planned in India are mentioned by the IEA and confirmed through our contacts [3, 81]. As can be seen in Table 6, data on the exact sizes, locations and technologies are not yet available. However, the plans seem very firm in that the Indian government is behind the initiative and various Indian oil companies, many state-owned, will be involved. Further, according to our sources two to three of the plants seem already to be under construction. The information regarding these plants are less concrete than for the other ones included, but were added since it may be an important initiative for future Indian developments.

Finally, for the Nordic market St1 plans three plants using wood feedstock. The company is currently operating a demonstration plant in Kajaani, Finland using the same technology [23, 27, 57].

Table 6 Planned large-scale advanced fermentation plants for the production of ethanol. Grey rows include more general, not plant specific, information. For complete references for data in this table, see the corresponding Table C6 in Appendix C.

Plant	Status	Feedstock	Product	Capacity GWh/y / [m^3/yr]
Fiberight Hampden (USA)	Under construction	MSW	Ethanol	134 (22 680)
COFCO Zhaodong (China)	Planned	Various lignocellulosics	Ethanol	374 (63 370)
Clariant x2 (Romania/Slovakia)	Under construction/Planned - 2020	Agricultural residue	Ethanol	2*374 (2*63 370)
St1 Cellunolix x3 (Scandinavia)	Planned - 2020	Wood	Ethanol	3*295 (3*50 000)
NordFuel Refinery (Finland)	Planned - 2022	Wood	Ethanol	487 (82 380)
Henan Nanyang 2 (China)	Planned	Crop residues	Ethanol	1 116 (189 000)
New Energy Spirit (USA)	Planned - 2021	Crop residues	Ethanol	357 (60 480)
Beta Renewables (Slovakia+USA+China)	Under construction (possibly on hold)	Agricultural residues/Energy grasses/wheat straw, corn stover	Ethanol	412+446+670 (69 710 + 75 600 + 113 400)
12 plants - various sites in India[1]	Early 2020:s	Various lignocellulosics	Ethanol	About 60 (10 000) each

[1] The Indian authorities plan 12 plants for advanced bioethanol production - actual sites, technologies and companies are, however, not yet published [3, 81].

In addition to the type of advanced fermentation technologies planned to be used in the plants described above, there are advanced fermentation and catalytic reforming technologies being developed to produce higher alcohols and hydrocarbons (VC6). However, these developments are mostly still at the demo-scale. One exception is the company Amyris, which in their plants produces various non-fuel chemicals, and the DSM plant in Brazil (former Amyris and thus Amyris technology), which produces farnesene. All these plants use sugar as feedstock, though.

Finally, there are also developments of further conversion of alcohols to hydrocarbons, e.g ethanol to jet fuels and methanol to gasoline. So far, there are no large-scale plants or plans for plants, based on an advanced conversion chain. Further, such processing would not increase total volumes of advanced biofuels available, only change the type of fuel.

4.3.3 Plants based on the value chain for hydrotreatment of fatty acids

There are large-scale ongoing plans for further expansion of HVO production, primarily by those large refinery actors that are already on the market with commercial plants. The pathway benefits from a number of factors – it is a large-scale technology, it can be well integrated into the industrial refinery infrastructure and consequently step-wise developed with – in comparison - limited amount of risk. It is, thus, driven by large-scale actors with needed financial resources and technological know-how. It also produces a drop-in fuel with a comparably high level of flexibility for the market development.

The back-side of the pathway is its reliance on sustainable fatty feedstock, and their limited potential. Most of the planned plants will, allegedly, be based on fatty waste materials, such as used cooking oils, animal fats and “non-edible” oils. However, technology-wise there is nothing that hinders use of virgin, edible, oils and the actual feedstock mix can be expected to depend on the development of both market and regulation. Since the potential of sustainable fat based feedstock is comparably limited, a very large expansion is dependent on the success of technological development to increase the feedstock portfolio to include also lignocellulosic material (see also Section 4.3.4).

Table 7 Planned large-scale plants for hydrotreatment of fatty acid feedstocks for the production of HVO etc. For complete references for data in this table, see the corresponding Table C7 in Appendix C.

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
Eni Gela (Italy)	Planned - 2018	Vegetable oils	HVO	7304 (764 330)
Eni Venice Expansion (Italy)	Planned - 2021	Vegetable oils, UCO, animal fats	HVO	852-1826 (89 170-191 080)
St1 Göteborg (Sweden)	Planned - 2021	Crude tall-diesel, other FOG	HVO	2435 (254 780)
Preem Expansion (Sweden)	Planned - 2023	Waste FOG, bio-oils based on forestry residues	Renewable diesel, gasoline and jet fuel	10 914 (1 080 000)
Neste Singapore Expansion	Planned - 2022	Various FOG	HVO	14607 (1 528 660)

SGP South Point (USA)	Planned - 2020	FOG	HVO	4334 (453 600)
Colabitoil (Sweden)	Planned - 2021	FOG	HVO	6086 (636 940)
Petrobras (Brazil)	Planned	-	HVO	2800 (292 990)
Petrixo (United Arab Emirates)	Planned	-	HVO	4869 (509 550)
Emerald Biofuels (USA)	Planned	Non-edible oils	HVO	3973 (415 800)

One group of developers stand out since they are specifically focusing on lignocellulosic feedstocks originating from forest residues. The plants they are planning, which thus are intended to be based on hydrotreatment of up-graded lignocellulosic materials, until now not used for biofuel production, are listed in Table 8. The actors consist primarily of industry that has a link to the Nordic countries and the forest industry and include UPM, SCA and Silva Green Fuels.

The three plants included in Table 8 are, thus, planned for including the entire value chain, from wood to fuel at the same site, including, of course, some kind of pretreatment steps. Silva Green Fuels has, for instance, a collaboration with Steeper, whose technology is based on a type of hydrothermal liquefaction using water super-critical conditions and called Hydrofaction™ [86]. The plants planned by Preem and St1, included in Table 7, are also intended to – at least partly – use feedstock based on forest residues, but pre-treated into different types of bio-oil intermediates elsewhere. Consequently, Preem and St1 are two important Nordic actors involved in the development of intermediate bioenergy carriers based on new feedstocks from the forest (see next section).

Table 8 Planned large-scale plants for hydrotreatment of up-graded lignocellulosic materials For complete references for data in this table, see the corresponding Table C8 in Appendix C.

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
SCA Östrand (Sweden)	Planned - 2024	Wood and black liquor	Renewable diesel+gasoline	3631 (359 280)
Silva Green Fuels (Norway)	Planned - 2023	Wood residues	Renewable diesel	1011-1516 (100 000-150 000)

UPM Kotka (Finland)	Planned - 2020	Wood biomass	Renewable fuels[1]	6051 [1] (598 800)

[1] UPM are vague about what type of fuels that will be produced here. The capacity number given here is calculated assuming product is diesel.

4.3.4 Plants for the production of intermediate bioenergy carriers

The value chain focusing on intermediate bioenergy carriers can include different types of technology pathways. Here, however, the focus is on developments relevant for the production of liquid biofuels. Therefore we have included three types of technologies for production of intermediates:

- Pretreatment of crude tall-oil – a fatty residue from forest industry - into tall diesel, used as a feedstock for final conversion into HVO since 2010.
- Fast pyrolysis - which is in principal commercial - that produce a bio-oil with high water and oxygen content, which cannot substitute fatty feedstocks for HVO production directly.
- Hydropyrolysis – also referred to as hydrothermal liquefaction (HTL) - and other thermal liquefaction technologies that can produce biooils with lower oxygen content, that could be more suitable for the production of HVO without further pretreatment in a refinery process. However, these technologies are at a lower TRL (Technology Readiness Level).[13]

Further, smaller-scale plants have been included than for the other value chains – partly, since the plants discussed here represent a more immature value chain and thus are closer to the demo scale, partly, since the idea of this value chain is that several, relatively, smaller-scale plants may serve a larger-scale plant for final fuel production. Finally, please note that Table 9 include both existing and planned production plants.

There exist currently three operational and commercial pyrolysis plants – one in Finland, one in the Netherlands and one in Canada [22, 23, 58]. Their products are currently all used for producing heat and/or power. However, they are also all developing and planning for including further up-grading steps that would make it possible to use the bio-oil as a feedstock in the refinery industry [23, 58, 59]. The plant in Canada is owned by the company Ensyn, which is one of the major actors involved in the future developments, with plans for the construction of three more plants in North and South America [22, 23, 60]. Ensyn presents its market solution as producing a "bio-crude", which can be mixed into a fluid catalytic cracking (FCC) unit at a fossil refinery, together with the fossil feedstock. The shares that can be substituted for biofuel feedstock depend on the quality of the bio-oil, but currently shares at about 5% are discussed [61].

Other developments listed here are primarily linked to the Nordic market and to different types of collaborations between the refinery and forest industries. In addition to the actual stand-

[13] Catalytic pyrolysis, without the use of H_2, is another technology, producing a bio-oil that in terms of product quality in general lies in-between the product from fast pyrolysis and that from (catalytic) hydropyrolysis.

alone, distributed plants included in the table below, similar pre-treating steps need of course to be included also in the developments planned by UPM, Silva Green Fuels and SCA Östrand above (see Table 8).

The large stand-alone expansion planned by Preem and included in Table 8, is partly linked to thesupply of feedstock from this type of plants for intermediate conversion [32]. Preem is therefore directly involved in several of the planned plants below – namely the Setra Pyrocell plant, Rottneros Renfuel, Biozin and the Sunpine expansion. One focus has been put on technology development to convert lignin to a viable feedstock for the HVO process, another to produce bio-oil of a quality that can be included in the refinery process in a similar way as current feedstocks.

Table 9 Plants for the production of intermediate bioenergy carriers for the production of transportation fuels. For complete references for data in this table, see the corresponding Table C9 in Appendix C.

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
Pretreatment of tall-oil				
Sunpine[1] (Sweden)	Operational	Crude-tall oil	Crude-tall diesel	100 000 m^3
Sunpine Expansion[1] (Sweden)	Planned - 2020	Crude-tall oil	Crude tall-diesel	60 000 m^3
SCA+St1 Tall-diesel[2] (Sweden)	Planned - 2021	Crude tall oil	Crude tall diesel	100 000 m^3
Fast pyrolysis				
Fortum Joensuu (Finland)	Operational	Forest residues	Crude bio-oil	264 (50 000)
Empyro (Netherlands)	Operational	Wood residue	Crude bio-oil	106 (20 000)
Ensyn Renfrew (Canada)	Operational	Forest residues	Crude bio-oil	59,9 (11 340)
Ensyn Cote-Nord (Canada)	Planned	Woody biomass	Crude bio-oil	209 (39 690)
Ensyn Brazil	Planned	Eucalyptus residues	Crude bio-oil	439 (83 600)

Ensyn Georgia (USA)	Planned	Mill and forest residues	Crude bio-oil	399 (75 600)
Setra Pyrocell plant[3] (Sweden)	Planned - 2021	Sawdust	Pyrolysis oil	26,4 kton
Hydropyrolysis and other types of thermal liquefaction				
Rottneros Renfuel[3] (Sweden)	Planned - 2021	Lignin (black liquor)	Lignin-oil	30 kton
Biozin[3,4] (Norway)	Planned - 2022	Wood	Bio-oil	5*120 Ml[4]
Suncarbon (Sweden)	Planned - 2022	Lignin (black liquor)	Lignin-oil	50 kton

[1] The SunPine product is currently used as feedstock for Preem's HVO production (see Table 3).
[2] Product intended as feedstock for St1's HVO production (see Table 7)
[3] Preem is directly involved in the technology development activities related to the Setra Pyrocell, Rottneros Renfuel and Biozin plants, as a strategy to increase the feedstock portfolio for its large-scale HVO expansion plans.
[4] Biozin plan five 120 Ml plants. The first one is planned for 2022. No start-up years are specified for the remaining four. Biozin and Preem announced in December 2018 a new collaborative agreement, including financial commitments [100].

5 GLOBAL ADVANCED LIQUID BIOFUEL PRODUCTION FROM NOW UNTIL 2030

5.1 ESTIMATE OF CURRENT ADVANCED BIOFUEL PRODUCTION

Based on the plant data presented in Section 4.2, the total amounts of advanced liquid biofuels currently produced have been estimated. This estimate is uncertain since, as noted above, data on actually produced volumes on plant level are in many cases difficult to obtain. For the estimate we have followed the definition of advanced biofuel production used in this report, and accepted definitions of waste and residues used in current regulation. As an example, ethanol from corn kernel fibre is considered as cellulosic feedstock in the US – where it is currently produced - and has thus been included as advanced biofuel. Further, all waste based fuels are, according to the same regulations, considered to have low iLUC risk, fulfilling the final condition for advanced biofuels. For other, more specific, assumptions, see notes below Table 10).

According to this plant based estimate (see Table 10), in total about 27 TWh/year (3.0 Mm^3/year) of advanced biofuels have been produced in 2016/17, excluding biofuel production based on PFAD as feedstock. This equals less than 3 % of total biofuel production and, thus, less than 0.1 % of total current energy use for transportation. If PFAD is classified as a waste based feedstock our estimate is that the total amount would instead be about 40 TWh/year (4.3 Mm^3/year). In 2018, additional production of, in total, about 3.5 TWh is expected to come on line.

Notably, 96-97 % of the advanced biofuels estimated above consists of HVO, which makes the estimate extremely sensitive both to the assumptions about which HVO feedstocks are included in the advanced biofuel definition and to data used on current feedstock composition and production levels in existing HVO plants (see notes below Table 10). Especially, the sustainability of PFAD as biofuel feedstock is debated and its treatment in national regulation varies. In some countries it is considered a waste feedstock and in others, like Norway, as a co-product of palm oil.[14] Within the proposed Renewable Energy Directive (RED II) of the EU, HVO from used cooking oil (UCO) and animal fat feedstocks are capped at 1.7 % of the 14 % target in 2030. However, production from other residual feedstocks, including tall oil and PFAD are not subject to this cap. As a consequence, we have included two estimates, depending on the classification of PFAD. Further, the data for India and China is even more uncertain than for other plants, why this production is specified separately.

The estimate presented here can be compared to the IEA estimate of advanced biofuel production. The IEA uses a definition of advanced biofuel production equivalent to the one used here. However, they distinguish also between advanced and *novel* advanced biofuel, and do not include HVO in the latter. Their estimate of global *novel* advanced biofuel production in 2017

[14] In Sweden, PFAD has been considered a waste feedstock and has thus high GHG reductions (about 88 %) in the sustainability reporting. However, in November 2018, the government decided to change its classification to co-product from July 1, 2019, which will also impact future reported GHG reduction data [101].

amounts to about 0.3 Mtoe or 3.5 TWh [3]. In IEA Renewables 2017 they include in this number HVO produced in plants using waste and residues only, but not plants with mixed production. In IEA Renewables 2018 they claim not to include HVO at all, but total production is similar and they do not refer to what this change implies explicitly [3, 15]. In any case, this estimate is considerably higher than the one in Table 10. One factor that may contribute to, but not explain, the difference is that we do not include production in demo-plants. Further, the IEA states that the utilization rates of the highest-performing novel advanced biofuel plants currently lies at 40-50 %, which is considerably higher than the data we have found. The IEA gives no explicit estimate on the share of advanced biofuel in total HVO production. However, it finds that 20 % of all biodiesel production in Europe is based on waste and residue feedstocks, which would be equivalent to roughly 26 TWh and quotes also Neste's share of waste and residues (including PFAD) in their global production, which would add about 10 TWh outside of Europe.

Table 10 Estimate of total production of advanced biofuels in 2016/2017 and expected additional production in 2018.

GWh/year (million litres/year)	Total estimate	Of which in China	Exkl PFAD	Additional 2018
Advanced ethanol production	980 (166)	260 (44)	980 (166)	80 (14)
Advanced HVO production	39 100 (4 100)	0	26 240 (2 800)	3 430 (360)
Total	**40 110 (4 266)**	**260 (260)**	**27 220 (2 966)**	**3 510 (374)**

The following assumptions have been used for calculating the estimate in Table 10:

- Actual production data are used for plants for which we have data.
- Total advanced (cellulosic) ethanol production in the US is based on renewable identification numbers (RINs) reported by the US EPS 2017.
- For ethanol production plants without data on actual production we have assumed utilization rate of 35 %, based on the best performing plant for which there is data.
- For HVO production in Neste plants available aggregated data on capacity utilization (98%) and share of waste feedstock, including PFAD (82 %), are used. The share of PFAD is assumed to be 45% of total waste based feedstock. (This assumption is based on Swedish sustainability reporting, and is thereby, due to the regulatory situation in Sweden, probably on the high side [16]).
- For HVO plants without data on actual production, a utilization rate of 80 % is assumed.
- Some HVO plants (Preem, UPM, Diamond Green), specifically claim that they only use waste based material, excluding PFAD. The feedstock shares for other plants have been estimated based on data available (e.g. 15 % UCO in the ENI plant). The Chinese plant is assumed to only use conventional feedstock.

- Additional production in 2018 includes production in the Enerkem plant in Canada, increased capacity and production at Preem in Göteborg, and production in the Total plant in LaMede (50% based on waste and residues).

5.2 METHODOLOGY FOR ESTIMATING FUTURE PRODUCTION

The potential for global advanced biofuel production presented here are based on the following basic presumptions:

- A general positive development for biofuels in terms of policy and regulation, based on the requirements of the Paris agreement. This is valid for both the low and high estimates presented below. A truly “low” estimate of the potential, assuming a negative market development, would be at today’s level or lower and not very interesting for the purposes of this report.
- On the other hand, the estimated production volumes are not based on the actual expected demand for biofuels or on the amounts needed to fulfil targets set, but rather directly on current industrial development plans identified. For the relatively short time period until 2030 this is also reasonable, since the development of production capacity, from initial planning until full production, takes at least five years. This means that a large share of production plants that will be operational by 2030 are already in the planning process.
- The feedstock potential for the production of advanced biofuel has not been explicitly taken into account for these estimates. However, at the levels of these estimates, and on the time frame in question, there is strong support in literature that these amounts can be sustainably provided. Estimates of sustainable feedstock potentials are in general considerably higher (3). Lack in technological developments, may, however, decrease the potential for sustainable feedstock for the HVO processes – a situation which is mirrored by the low scenario.
- Other factors that influence the development of advanced biofuel production, such as detailed policy development, oil and energy price development, development of batteries and electric power trains, economic development etc, etc are not considered for this estimate (see also next section). Implicitly, some of those factors may be the ones influencing developments towards the low or high ends of the span.

More specifically we have used the tables of large-scale existing, idle and planned production plants and made generalized assumptions regarding their realization and operation (see Table 11). In these assumptions we have not specified which plants that are expected to be realized and which not. A discussion relating results to the plausibility of different plans being realized is, however, included in Section 5.2. Most development plans included in Chapter 4, concern plans for construction in the early 2020:s. If these plans are realized it is likely that additional plants will be constructed between 2025 and 2030. In the base case, we are not making any assumptions about such additional capacity. In Figures 8 and 9, however, a potential continued development curve is indicated.

It should also be noted here that, in general, published development plans are highly uncertain and often subject to delays, changes and cancellations, and mostly only a smaller share of the plans are realized.

Table 11 Plant assumptions for low and high development estimates. The low levels of capacity utilization assumed for HVO (in Scenario Low) reflect assumptions on availability/use of *sustainable* feedstock (including lignocellulose, waste and residues). Regarding data for 2018, see Table 10.

	Start-year	Percentage of capacity	
		Low	**High**
Operational plants	2019	60 % for ethanol, 80 % from 2021 70% for HVO	100%
Idle plants	2020	50 %	100%
Plants with planned year ≤ 2020	2022	60% for ethanol and other, 80 % from 2025 30% for HVO	100%
Plants with planned year ≤ 2022	2024	60% for ethanol and other, 80 % after 3 yrs 15% for HVO	100%
Plants with planned year ≥ 2023	2025	As above	100%

Notes on the assumptions described in Table 11:

- Percentages describe assumed utilization rate based on feedstocks included in the advanced biofuel definition.
- Current share of waste and residue feedstocks for HVO production has been estimated to 70%, and is assumed to remain on this level for existing plants in Scenario Low (see also Table 10). For new plants, lower shares are assumed (in Scenario), because of limitations in available advanced feedstock.
- Of total advanced HVO production (based on waste and residues), about 33 % have been assumed to currently be based on PFAD (see Table 10). This share is assumed to remain over the entire period.
- Plants for which the start-year is not specified have been assumed to be built 2023 or later.

Biofuel production in China and India has been presented separately, mainly since data availability about the development plans there are lower and therefore numbers are more uncertain, but also since the production is less likely to be available on the global market and to a higher extent produced directly for domestic use.

5.3 ESTIMATE OF POTENTIAL BASED ON PLANS FOR PLANT DEVELOPMENT

When applying the assumptions in Table 11 for all operational, idle and planned plants in Appendix C, the development of global advanced biofuel production evolves as illustrated in Figures 8 and 9, for respective scenario. The dotted areas outline a potential continued development after 2025, in addition to the plants identified.

Scenario High represents a maximal case, based on the plants identified, and is primarily useful for giving the order of magnitude (see Figure 8). The total amount is equivalent to about 9.4 Mm^3 (85 TWh), or 6.9 Mm^3 (61 TWh) without fuel based on PFAD as feedstock, in 2023 and about 16.4 (149) and 11.9 Mm^3 (106 TWh), respectively, in 2030. For the early years of the period this can be expected to almost certainly overestimate development, since it is quite unlikely that all plants are realized and produce at maximum capacity. Towards the mid-twenties and later, new development plans can evolve, and more plants be constructed. This might be especially true in areas like India and China where we now see increasing ambitions but so far few details on concrete plans.

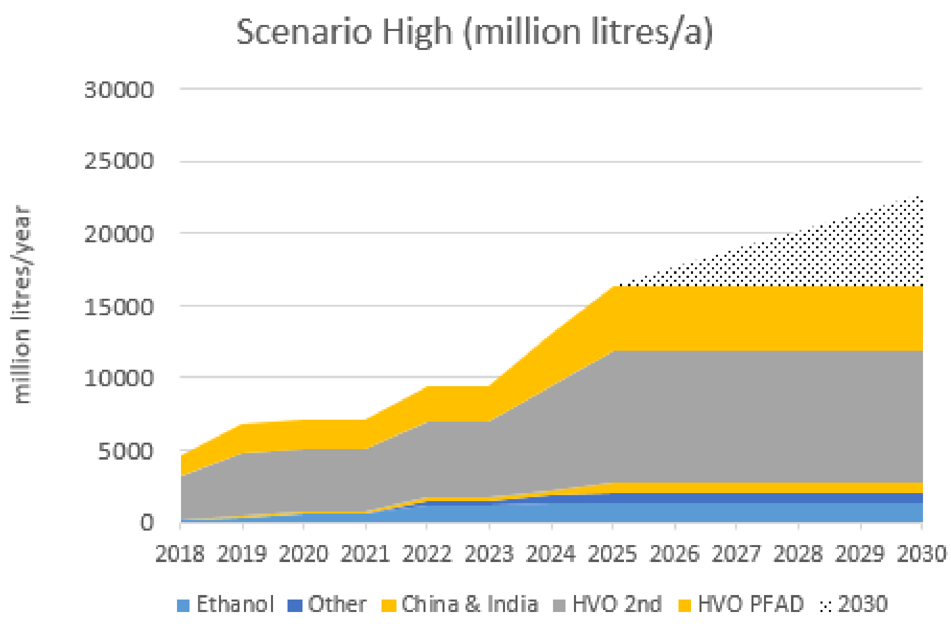

Figure 8 Development of global advanced biofuel production, according to Scenario High. The dotted area represent a potential increase from the year 2025, with a continued development of plants at similar rates as before. This production is above the plant inventory and not linked to any specific plants. This figure is available in GWh/a in Appendix D.

The development in Scenario Low represents more of a plausible production development, based on the plants and plans identified. Here, the total amount equals instead about 6.0 Mm^3 (54 TWh), or 4.4 Mm^3 (39 TWh) without fuel based on PFAD as feedstock, in 2023 and almost 11.5 and 8.4 Mm^3 (104 and 74 TWh), respectively, in 2030. The 2030 levels would in volumes be equal to about 6 Mm^3 HVO (without PFAD based HVO), 1.4 Mm^3 ethanol and 0.68 Mm^3 other fuels mostly based on thermochemical conversion (assuming also these are some kind of diesel-like fuels).

Even though, in this case, a smaller share of future HVO production is assumed to be based on sustainable feedstocks, like waste and residues, this development still involves a large increase in advanced HVO production. It can be compared to an estimate by the IEA that availability of waste oils and fats (probably including PFAD) may allow for HVO from these feedstocks to cover 6-8 % of global biofuel production [3]. This amount would (assuming it is related to today's biofuel production) be equal to about 58-78 TWh (6.1-8.2 Mm^3 HVO). If this estimate is correct, production above these levels would depend on the success of technology developments to produce intermediate feedstocks for HVO-type production from lignocellulosic material (see Section 4.3.4).

The production of advanced biofuels other than HVO consists of ethanol production based on fermentation of lignocellulosic feedstocks and the production of other advanced biofuels through thermochemical conversion (see Figure 10). The latter being mostly production of FT-diesel or other diesel-like fuels trough gasification, but also one plant planned for methanol production (planned to provide feedstock for production of chemicals). The plants planned in China and India also consist mainly of advanced ethanol production.

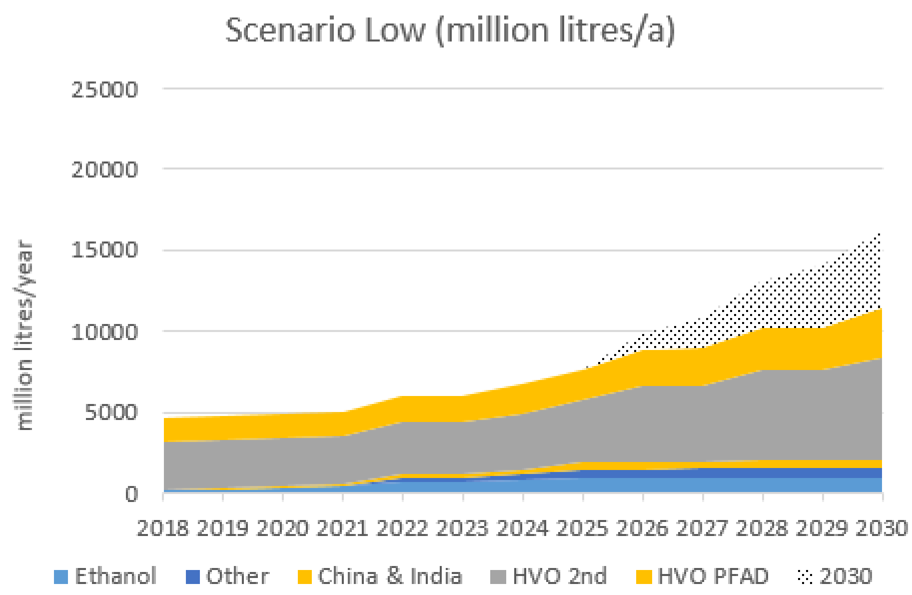

Figure 9 Development of global advanced biofuel production, according to Scenario Low. The dotted area represent a potential increase from the year 2025, with a continued development of plants at similar rates as before. This production is in addition to the plant inventory and not linked to any specific plants. This figure is available in GWh/a in Appendix D.

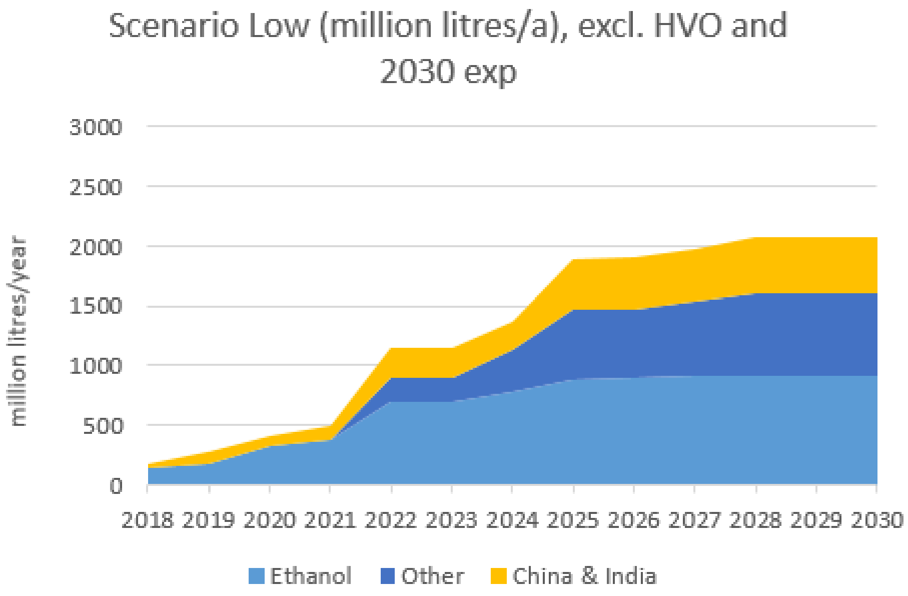

Figure 10 Development of global production of advanced biofuels other than HVO, according to Scenario Low. In Scenario High total production in 2030 amounts to 2.7 Mm^3. This figure is available in GWh/a in Appendix D.

It should be noted, again, that these estimated developments are made by assuming general utilization rates (see Table 11), and not by assuming the realization of specific plants. However, it may be interesting to compare the resulting volumes with the planned capacities of those plants that may have a somewhat higher realization probability:

- Advanced fermentation, and other, plants for the production of ethanol, except in China (total of 0.9 Mm^3 ethanol 2030 in Scenario Low)
    - Full utilization of operational plants as well as re-start of two of the currently idle plants – additionally roughly 0.3 Mm^3 (capacity).
    - The Fiberight Hampden and Clariant plants currently under construction – about 0.09 Mm^3 (capacity)
    - The three St1 Cellunolix plants planned for 2020 – 0.15 Mm^3 (capacity).
    - In addition advanced ethanol production in Enerkems existing and planned gasification plants in Canada – 0.08 Mm^3 (capacity).
- Advanced fermentation, and other, plants for the production of ethanol in China and India (total of 0.48 Mm^3 ethanol 2030 in Scenario Low)
    - Full utilization of operational plants – additionally about 0.08 Mm^3
    - The COFCO plant planned for “2018” and the Henan Nanyang plant (having two operational plants before) – 0.25 Mm^3 (capacity)
    - All 12 Indian planned plants – 0.12 Mm^3 (capacity)
- Gasification plants for the production of other advanced biofuels, such as FT-diesel and methanol (total of 0.68 Mm^3 biofuel 2030 in Scenario Low)
    - The RedRock and Fulcrum plants under construction in the US – 0.057 Mm^3 (capacity)

    - The Enerkem plant in the Netherlands, having earlier experience from large scale plant – 0.28 Mm^3 methanol (capacity)
    - The planned BioTfuel plant in France, with large industrial actors behind it – 0.24 Mm^3 FT-diesel (capacity)
- Hydrotreatment plants for the production of HVO (total of 6.3 Mm^3 2030, excl PFAD, in Scenario Low)
    - Planned production plants of the industrial actors already having operational HVO plants (ENI, Neste, Preem, UPM) and St1 – total of almost 4.5 Mm^3 (capacity)

5.4 GLOBAL AND EUROPEAN DEMAND FOR ADVANCED BIOFUELS IN 2030

There are several studies aiming at determining the future development of biofuel production. On the global level we have chosen to use the IEA studies for a comparison with the outlook above. The comparison includes two different types of IEA studies, having different time perspective and different purposes and, thus, using different methodologies. Firstly, the Renewables studies in the Market Report Series aim to give a *prognosis* for the next five years – for Renewables 2018, the period of 2018-2023. This prognosis is based on similar plant information as used above, but also on policy developments in various regions of the world, more general national plans for expansion (e.g. in India), economic development aspects, etc [3, 15].

Secondly, the IEA Technology Roadmaps aim at describing the *developments needed* in order to fulfil various climate change scenarios and mirror the long-term pathway from the current system until 2060. These roadmaps are based on modelling of the energy system under restricted emissions of GHG, and include assumptions about technology cost and performance developments, available feedstocks, deployment rates and interaction between different parts of the energy system. Here we have used the bioenergy roadmap from 2017 and its 2DS scenario (consistent with a 50 % chance of limiting future global average temperature increases to 2ºC by 2100) [102]. In the first years, the long term development is made to coincide with the short-term prognoses described above.

The short-term prognosis of biofuel production in IEA Renewables 2018 include partly conventional biofuel production, partly novel advanced biofuel production (see Figure 11). In this division HVO production – both based on conventional and advanced feedstocks – is included in conventional biofuel production. Consequently there is no prognosis that directly mirrors the total estimate made in this study. However, for the novel advanced biofuel production – including cellulosic ethanol and thermochemically produced diesel – the prognosis for 2023 can be compared with the development in Figure 10. The IEA prognosis lies between 11 and 18 TWh/yr (main and accelerated case) in 2023, while the estimate in this study is about 7.7 TWh/yr (1.15 Mm^3) in Scenario Low, increasing to 13.9 (2.07) until 2030 (corresponding numbers for the Scenario High being 12.2 (1.81) and 18.1 (2.70), respectively). It should be noted that IEA expect 18 % of project developments to take place in India. Also, China has set a target to produce 300 Mton (roughly equivalent to 1600-2800 TWh, depending on type of fuel) of advanced biofuels by 2020 [1].

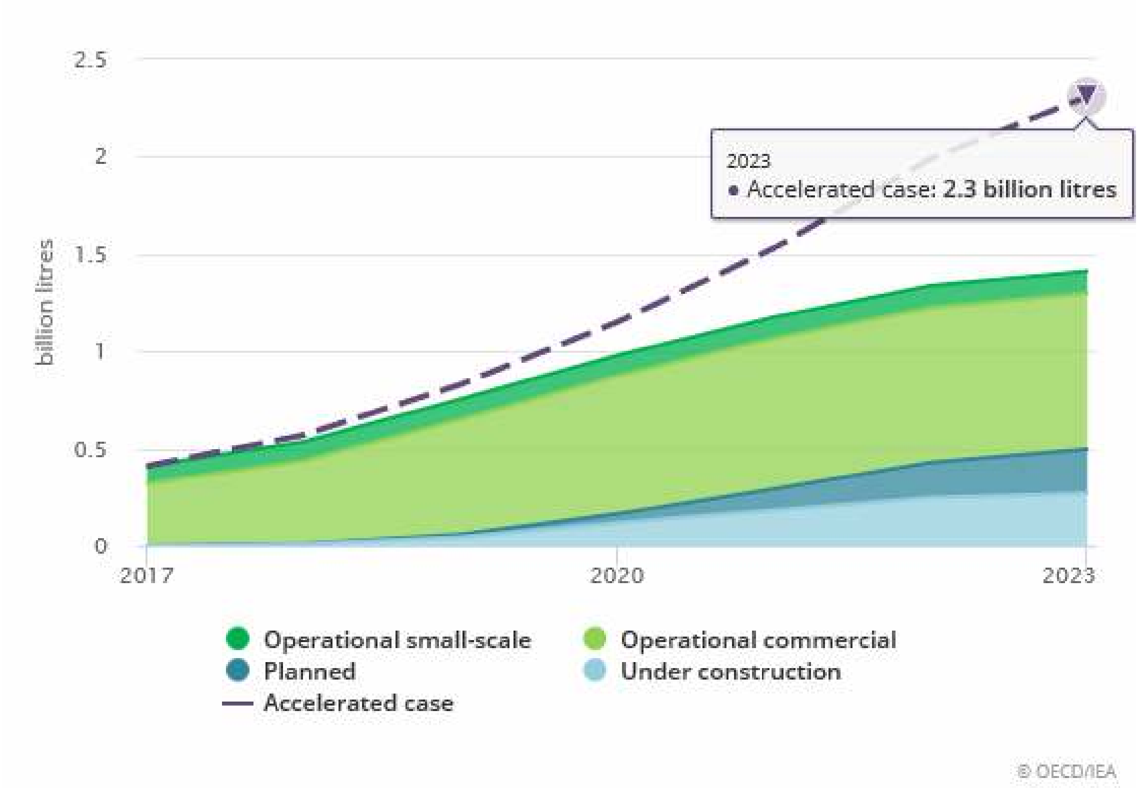

Figure 11 Prognosis of global novel advanced biofuel production, © OECD/IEA Renewables 2018 [3].

In the longer-term IEA comes to the result that advanced biofuel production needs to increase to about 8 000 TWh (about 29 EJ), of which the major share consists of advanced biofuels (including HVO type fuels). The strong increase in advanced biofuel production is then expected to start from about 2030. It should also be noted that this is in context of a slight decrease in total final energy use for transportation, which is provided for through more than 40 % fossil conventional fuels; slightly above 25 % electricity and the rest biofuels.

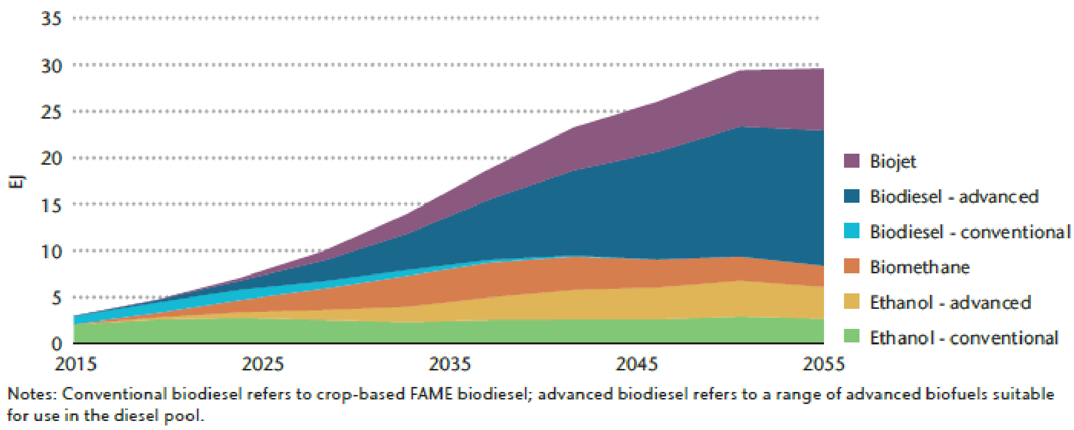

Figure 12 Development of long-term global biofuel demand by fuel type according to IEA bioenergy roadmap, and for their 2 DS scenario © OECD/IEA Technology Roadmap [102].

On the European scale, there is a fairly recent study published by the compiled by Ecorys and published by the European Commission [1]. In this report they conclude that about 50 % of transport energy demand in 2050 can be provided by advanced biofuel mainly based on domestic feedstock. The conclusion is also that, in the long run, technology pathways based on gasification and pyrolysis will play the major role, as a result of being the most flexible biofuel production technologies. They expect, that development accelerates after 2030, describing a production capacity of about 170 TWh in 2030 and 1440 TWh in 2050, for the HIGH scenario and using a operations time of 6000 hours. These numbers can be compared to the ambition set out in the implementation plan for the updated European strategic energy plan (SET-plan), in which targets for 25 TWh in 2022 and 200 TWh in 2030 are included [103].

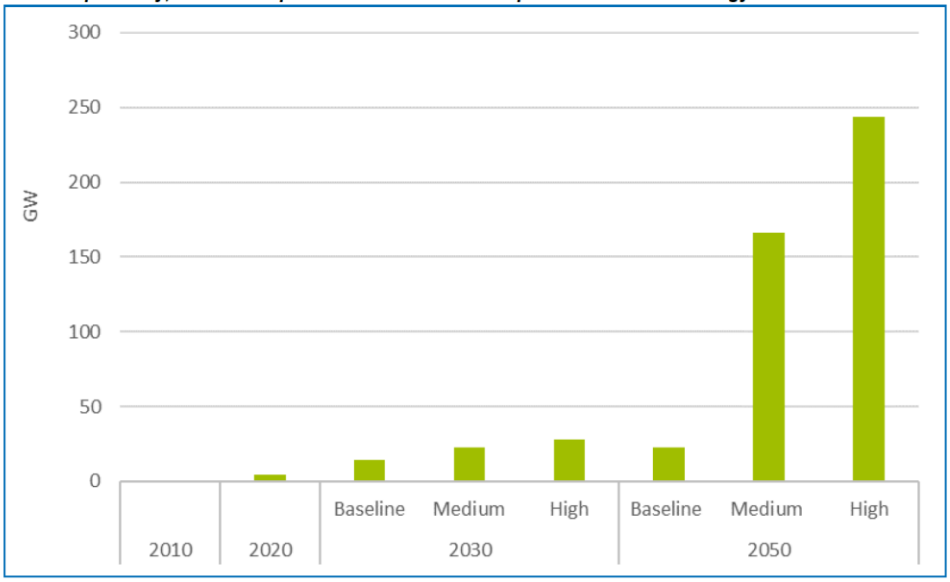

Figure 13 Development of advanced biofuel production capacity in Europe, based on an analysis of capacity needed, according to the EcoRys report to the European Commission. [1]

5.5 STATUS OF DEVELOPMENT – IN SUMMARY

The regulatory developments in all regions of the world will be fundamental to investments being made and potential increase in advanced biofuel production. The outlook for such developments has not been included at all in this study. One could note, however, that internationally policies aiming at increasing biofuel shares are getting stronger and that, on the European level, the policy situation is, with the expected finalization of the RED II, more stable than it has been for the last five to eight years. Here, the focus is on technologies that may significantly increase availability of advanced biofuels in the relatively short period until 2030.

Gasification of biomass for production of liquid biofuels seem to have had a somewhat decreasing momentum lately, possibly linked to the strong focus on HVO. The main argument for gasification is the flexibility in feedstock and products produced – from methanol and DME to FT-diesel. There are still quite a few plans for new plants within the next few years and if these are realized the development might be accelerated, since the technologies are well proven on the larger demoscale. Other studies, focusing on the longer term, beyond 2030, identify gasification as one of the main options for large-scale increases in biofuel production.

Internationally, there is a continued strong focus on ethanol as the most dominant biofuel, for transportation and on developing production capacity of advanced ethanol production. This deserves to be pointed out, since over the last few years there has been a strongly declining interest for ethanol in the Nordic countries. The technology is on the verge of being commercial, having had a construction “boom” already, with a number of plants operational and quite a few development plants. Apart from the today dominating countries of Brazil and the US, there are also ambitious plans for development in both China and India. Yet, current plants have very low utilization rates due to both technological and economic reasons and the contribution until 2030 (based on available specific planned plants) is fairly limited.

The development of production capacity for advanced biobased diesel fuels has over the last few years increased strongly as a result the HVO development. For the future, product flexibility is expeted to increase and the technology will be increasingly relevant also for gasoline drop-in and jet fuel production. It is, however, often not included in data on current or future advanced biofuel production. This is a commercial technology, when based on fatty waste and residues. There is still a potential for increased production volumes based on currently used technologies, but the feedstock potential suitable for this technology is ultimately limited. To increase production beyond that technological development that can increase the feedstock flexibility is needed. Such technology developments aiming at producing bio-oils from e.g. wood residues, that have the right chemical qualities to be used as feedstock for HVO, are ongoing – especially in the Nordic countries and in Canada. However, most of these technologies are yet unproven in industrial scale.

REFERENCES

[1]: Research and innovation of the mid- and long-term potential for advanced biofuels in Europe, Baker P. et al, DGRES EC, november 2017

[2]: Biofuels for transport, Tracking Clean Energy Progress, OECD/IEA, 23 May 2018

[3]: © OECD/IEA IEA Renewables 2018 – Analysis and forecasts to 2023, IEA Publishing. Licence: www.iea.org/t&c

[4]: EIA, U.S. Energy Information Administration, https://www.eia.gov/beta/international/data/browser [Online]

[5]: EBB, European Biodiesel Board, http://www.ebb-eu.org/stats.php/ retrieved 18-11-05

[6]: REN21, 2018, Renewables 2018 Global status Report (Paris, REN21 Secretariat) http://www.ren21.net/gsr-2018/.

[7]: USDA; United States Department of Agriculture, EU Biofuels Annual 2018

[8]: Eurostat, Statistics database, [Online], Available: https://ec.europa.eu/eurostat/data/database

[9]: UNICA, Brazilian Sugarcane Industry Association, http://www.unica.com.br/

[10]: ePure, European Renewable Ethanol Association, https://www.epure.org/

[11]: IRENA, The Renewable Route to Sustainable Transport – A working paper based on Remap, August 2016, International Renewable Energy Agency

[12]: BP Statistical Review of World Energy, 67th edition, British Petroleum, 2018

[13]: RFA, Renewable Fuel Association, Markets & Statistics, the USA [Online], Available: https://ethanolrfa.org/resources/industry/statistics/

[14]: GREET, The Greenhouse Gases, Regulated Emissions, and Energy Use In Transportation Model, GREET 1.8d.1, developed by ArgonneNational Laboratory, Argonne, IL, released August 26, 2010. http://greet.es.anl.gov/

[15]: © OECD/IEA IEA Renewables 2017 – Analysis and forecasts to 2022, IEA Publishing. Licence: www.iea.org/t&c

[16]: Energimyndigheten, ER 2018:17 ”Drivmedel 2017 redovisning av uppgifter enligt drivmedelslagen och hållbarhetslagen”, Swedish Energy Authority, Sweden, 2018

[17]: Börjesson et al, ”Dagens och framtidens hållbara drivmedel”, Report f3: 2013:13, Sweden 2013, English summary available at: https://f3centre.se/sv/forskning/dagens-och-framtidens-hallbara-biodrivmedel/

[18]: Berglin and Schenck, Mapping of Biofuels R&D in Brazil, Sweden, 2012. Available: https://f3centre.se/sv/forskning/kartlaggning-av-biodrivmedel-i-brasilien/

[19]: ETIP Bioenergy, European Technology and Innovation Platform, Value chains applying advanced conversion technologies. Available: http://www.etipbioenergy.eu/value-chains/conversion-technologies/advanced-technologies

[20]: Energimyndigheten, ER 2016:29 ”Marknaderna för biodrivmedel 2016”, Swedish Energy Authority, Sweden, 2016

[21]: Chalmers (2018) GoBiGas demonstration – a vital step for a large-scale transition from fossil fuels to advanced biofuels and electrofuels. Thunman H, editor. Gothenburg, Sweden.

[22]: a. International Energy Agency Task33 "Database – Gasification of biomass and waste", [Online]. Available: http://task33.ieabioenergy.com/content/taks_description
b. International Energy Agency Task34 "Pyrolysis demoplant database", [Online]. Available: http://task34.ieabioenergy.com/publications/pyrolysis-demoplant-database/
c. International Energy Agency Task39 "Database on facilities for the production of advanced liquid and gaseous biofuels for transport", [Online]. Available: https://demoplants.bioenergy2020.eu/

[23]: I. Landälv, "Building up the future – Technology status and reliability of the value chains", Sustainable transport forum – Sub group on advanced biofuels, 2017.

[24]: Bioenergitidningen, ”122 anläggningar för produktion av biodrivmedel i norden”, *Bioenergitidningen,* nr 5-2018, pp. 30-34, Sept. 2018.

[25]: Greenea, ”New players join the HVO game”, 2017. [Online]. Available: https://www.greenea.com/publication/new-players-join-the-hvo-game/ Retrieved: 2018-11-14

[26]: K. Moriarty, A. Milbrandt, E. Warner, J. Lewis and A. Schwab, ”2016 Bioenergy Industry Status Report”, National Renewable Energy Laboratory, Golden, USA, 2018.

[27]: C. Chudziak, G. Alberts and A. Bauen, ”Ramp up of lignocellulosic ethanol in Europe to 2030”, E4tech Ltd, London, United Kingdom, 2017.

[28]: US Department of Energy's Bionergy Technologies Office, ”Alternative Aviation Fuels: Overview of Challenges, Opportunities, and Next Steps”, 2017. [Online]. Available: https://www.energy.gov/sites/prod/files/2017/03/f34/alternative_aviation_fuels_report.pdf Retrieved: 2018-11-14

[29]: A. Miles, ”Waste as a valuable resource for making high-grade biofuels”. Presentation held at the Advanced Biofuels Conference (Gothenburg), September 2018.

[30]: G. Kutas, ”Industry development of sugarcane ethanol in South America”. Presentation held at the Svebio Advanced Biofuels Conference (Gothenburg), September 2018.

[31]: M. Jahunen, ”Beyond fossils – Exploring the limitless opportunities in Bioeconomy”, presentation held at the Svebio Advanced Biofuels Conference (Gothenburg), September 2018.

[32]: P. Holland, ”Preem renewable transportation fuels production – Priorities and plans for an exciting future”, presentation held at the Svebio Advanced Biofuels Conference (Gothenburg), September 2018.

[33]: D. Szeezil, ”Commercial scale renewable transportation fuels”, presentation held at the Svebio Advanced Biofuels Conference (Gothenburg), September 2018.

[34]: T. Ekbom, ”Rapid climate change as driver for biofuels?”, presentation held at the Svebio Advanced Biofuels Conference, September 2018.

[35]: F. Burton ”No carbon left behind”, presentation held at the Svebio Advanced Biofuels Conference (Gothenburg), September 2018.

[36]: L. Waldheim, I. Landälv, "Building up the future – Cost of Biofuel", Sustainable transport forum – Sub group on advanced biofuels, 2017.

[37]: Enerkem, "Enerkem begins commercial production of cellulosic ethanol from garbage at its state-of-the-art Edmonton biofuels facility". [Online]. Available: https://enerkem.com/newsroom/?communique_id=122562 Retrieved: 2018-11-14

[38]: Edmonton Journal, ”Five minutes from trash to ethanol”. [Online]. Available: https://edmontonjournal.com/business/local-business/five-minutes-from-trash-to-ethanol-edmontons-long-delayed-enerkem-plant-explained Retrieved: 2018-11-14

[39]: Biomassmagazibe, ”Versalis buys Biochemtex, Beta Renewables”, [Online]. Available: http://biomassmagazine.com/articles/15632/versalis-buys-biochemtex-beta-renewables Retrieved: 2018-11-14

[40]: Ethanol Producer, ”Court accepts $48.5M bid for Abengoa Hugoton from Synata Bio”, [Online]. Available: http://www.ethanolproducer.com/articles/13947/court-accepts-48-5m-bid-for-abengoa-hugoton-from-synata-bio Retrieved: 2018-11-14

[41]: Agriculture.com, ”DuPont closes Iowa cellulosic ethanol facility, puts plant up for sale”, [Online]. Available: https://www.agriculture.com/news/business/dupont-is-selling-iowa-cellulosic-ethanol-facility Retrieved: 2018-11-14.

[42]: Compilation of presentations given at Miljødirektoratet, Oslo, Norway. 2018-10-09.

[43]: ETIP Bioenergy, ”Factsheet Borregaard”, 2018. [Online]. Available: **http://www.etipbioenergy.eu/images/Factsheet_Borregaard_final.pdf** Retrieved: 2018-11-14

[44]: A. Sherrard, “Leveraging on over a century of cellulosic ethanol experience”, Bioenergy International, No. 4 September 2018

[45]: Aditya Birla, ”Sustainability Report Domsjö Fabriker AB FY18”, 2018. [Online]. Available: http://www.domsjo.adityabirla.com/en/Documents/sustainability_report.pdf Retrieved: 2018-11-14

[46]: Neste, ”Neste Annual Report 2017”, 2018. [Online]. Available: https://www.neste.com/corporate-info/news-inspiration/material-uploads/annual-reports Retrieved 2018-11-14

[47]: Preem, ”Preem Årsredovisning 2017”, 2018. [Online]. Available: https://www.preem.se/globalassets/om-preem/finansiell-info/arsredovisningar/preem-ar-2017_sv.pdf Retrieved: 2018-11-14

[48]: Enerkem, ”Projects and partnerships”. [Online]. Available: https://enerkem.com/facilities/projects-and-partnerships/ Retrieved: 2018-11-14

[49]: Enerkem, “Partners agree on initial funding to kick off waste-to-chemistry project in Rotterdam”. [Online]. Available: https://enerkem.com/newsroom/?communique_id=122566 Retrieved: 2018-11-14

[50a]: Red Rock Biofuels, ”Lakeview Site”. [Online]. Available: https://www.redrockbio.com/lakeview-site.html Retrieved: 2018-11-14.

[50b]: Red Rock Biofuels, ”Process Technology Platform”. [Online]. Available: https://www.redrockbio.com/technology.html Retrieved: 2018-11-14

[51]: M. Ebadian, J. Saddler and J. McMillan ”IEA task 39 Newsletter issue 49”, International Energy Agency, 2018. [Online]. Available: http://task39.sites.olt.ubc.ca/files/2018/10/IEA-Bioenergy-Task-39-Newsletter-Issue-49-.pdf Retrieved: 2018-11-14

[52]: Biofuelsdigest, ”Commercial time – Aemetis embarks on $158 million cellulosic ethanol project in California”, 2018, [Online]. Available: https://www.biofuelsdigest.com/bdigest/2018/03/08/commercial-time-aemetis-embarks-on-158-million-cellulosic-ethanol-project-in-california/ Retrieved: 2018-11-29

[53]: N. Ullrich and M. Hequet, ” The BioTfueL project– An advanced B-XTL technology”. Presentation held at the 9th International Freiberg Conference, June 2018. Available: https://tu-freiberg.de/sites/default/files/media/professur-fuer-energieverfahrenstechnik-und-thermische-

rueckstandsbehandlung-16460/publikationen/11-02-the_biotfuel_project.norbert_ullrich.pdf Retrieved: 2018-11-14

[54]: Clariant, ”Groundbreaking for Clariant’s Sunliquid cellulosic ethanol plant in Romania”, [Online]. Available: https://www.clariant.com/en/Corporate/News/2018/09/Groundbreaking-for-Clariantrsquos-sunliquidreg-cellulosic-ethanol-plant-in-Romanianbsp Retrieved: 2018-11-14

[55]: Biofuelsdigest, “Fiberight now expects Maine plant to be read in March, or May”, 2018, [Online]. Available: https://www.biofuelsdigest.com/bdigest/2018/11/20/fiberight-now-expects-maine-plant-to-be-ready-in-march-or-may/ Retrieved: 2018-11-29

[56]: Fiberight, “Technology – Converting solid waste to energy”, [Online]. Available: https://fiberight.com/technology/ Retrieved: 2018-11-29

[42]: Compilation of presentations given at Miljødirektoratet, Oslo, Norway. 2018-10-09.

[58]: Ensyn, ”Ontario Facility”, [Online]. Available: http://www.ensyn.com/ontario.html Retrieved: 2018-11-14

[59]: https://www.fortum.com/media/2018/04/fortum-and-valmet-take-development-bio-oil-transportation-fuels-new-level

[60]: Ensyn, ”Georgia Project”, [Online]. Available: http://www.ensyn.com/georgia.html Retrieved: 2018-11-14

[61]: http://www.ensyn.com/refinery-feedstocks.html

[62]: Poet-DSM, ”Project Liberty”. [Online]. Available: http://poetdsm.com/liberty Retrieved: 2018-11-14

[63]: Gevo, ”Technology”. [Online]. Available: https://gevo.com/technology/ Retrieved: 2018-11-14

[64]: G. Kutas, ”Industry development of sugarcane ethanol in South America”. Presentation held at the Svebio Advanced Biofuels Conference (Gothenburg), September 2018.

[65]: Biofuelsdigest, ”Brazil’s CTC to build $38.5 million cellulosic ethanol add-on plant”, [Online]. Available: https://www.biofuelsdigest.com/bdigest/2012/12/10/brazils-ctc-to-build-38-5-million-cellulosic-ethanol-demo-add-on-plant/ Retrieved: 2018-11-14

[66]: C. C. Long and Y. W. Lee, ”Sourcing and processing low carbon feedstocks – latest development and requirements for suppliers”, Presentation held at the ISCC Shanghai Conference, July 2018. Available: https://www.iscc-system.org/wp-content/uploads/2018/01/Sourcing-Processing-Low-Carbon-Feedstocks-Latest-Developments-Requirements-for-Suppliers.pdf Retrieved: 2018-11-14

[67]: UPM, ”UPM Annual Report 2017”, 2018. [Online]. Available: http://assets.upm.com/Investors/2018/UPM_Annual_Report_2017.pdf Retrieved: 2018-11-14

[68]: Eni,”Biorefineries”, [Online]. Available: https://www.eni.com/en_IT/operations/mid-downstream/refining-marketing/biorefineries.page?lnkfrm=serp Retrieved: 2018-11-14

[69]: Eni, ”Integrated annual report 2017”, 2018. [Online]. Available: https://www.eni.com/docs/en_IT/enicom/publications-archive/publications/reports/rapporti-2017/Integrated-Annual-Report-2017.pdf Retrieved: 2018-11-14

[70]: Diamond Green Diesel, ”Welcome to Diamond Green Diesel”, [Online]. Available: https://www.diamondgreendiesel.com/ Retrieved: 2018-11-14

[71]: Renewable Energy Group, ”Renewable Energy Group Annual Report 2016”, 2017. [Online]. Available:

http://www.annualreports.com/HostedData/AnnualReportArchive/r/NASDAQ_REGI_2016.pdf Retrieved: 2018-11-14

[72]: Preem, ”Satsning på förnybar diesel är viktigare än någonsin”, [Online]. Available: https://www.preem.se/om-preem/insikt-kunskap/gronare-drivmedel/satsning-pa-fornybar-diesel-ar-viktigare-an-nagonsin/ Retrieved: 2018-11-14

[73]: B. Sherbacow, ”Wet and gaseous feedstocks: Barriers and opportunities”, presentation held at Berkeley, June 2017. Available: https://www.energy.gov/sites/prod/files/2017/07/f35/BETO_2017WTE-Workshop_BryanSherbacow-AltAir.pdf

[74]: Total, ”La Mede: a forward-looking facility”, [Online]. Available: https://www.total.com/en/energy-expertise/projects/bioenergies/la-mede-a-forward-looking-facility

[75]: L. Waldheim and F. Girio, “Bioenergy and biofuels – Conversion technology developments”, Presentation held at ETIP Bioenergy 8th Stakeholder Plenary Meeting, April 2018. Available: http://www.etipbioenergy.eu/stakeholder-plenary-meetings2/spm8-2018/ Retrieved: 2018-11-14

[76]: Fulcrum Biofuels, ”Facilities”. [Online]. Available: http://fulcrum-bioenergy.com/facilities/ Retrieved: 2018-11-14

[77]: Kaidi, ”Biodiesel”. Online. [Available]: http://www.kaidi.fi/english#biodiesel-en Retrieved: 2018-11-14

[78]: Biofuels-news, ”Worlds first commercial second-generation bioethanol facility shuts down”, [Online]. Available: https://biofuels-news.com/display_news/13070/worlds_first_commercial_secondgeneration_bioethanol_facility_shuts_down/ Retrieved: 2018-11-14

[79]: Kanteleen Voima, ”Biorefinery”, [Online]. Available: http://nordfuel.fi/en/biorefinery/ Retrieved: 2018-11-14

[80]: New Energy Blue, ”New Energy Spirit Biomass Refinery”, [Online]. Available: https://newenergyblue.com/projects/ Retrieved: 2018-11-19

[81]: SG Preston, ”SG Preston announces world’s largest purpose-built renewable diesel plant in Southern Ohio”, [Online]. Available: https://sgpreston.com/news-detail/18 Retrieved: 2018-11-14

[82]: Colabitoil, ”Fabrik Norrsundet”, [Online]. Available: https://www.colabitoil.com/verksamhet/fabrik-pilot/ Retrieved: 2018-11-14

[83]: St1, ”St1 plans to extend its advanced biofuels production”, [Online]. Available: https://www.st1.se/st1-plans-extend-its-advanced-biofuels-production-renewable-diesel Retrieved: 2018-11-14

[84]: St1, ”Gemensamt pressmeddelande från St1 och SCA”, [Online]. Available: https://www.st1.se/gemensamt-pressmeddelande-fran-st1-och-sca Retrieved: 2018-11-14

[85]: Miljökraft i Sverige AB, ”SCA Biorefinery Östrand AB: Samrådsunderlag för ett bioraffinaderi vid Östrands industriområde, Timrå kommun”, 2018. [Online]. Available: https://www.sca.com/globalassets/fornybar-energi/handingar/bioraffinaderi/samradsunderlag-bioraffinaderi-ostrand-6-mars-2018.pdf Retrieved: 2018-11-14

[86]: Steeper Energy, ”Steeper Energy announces EUR 50.6 M (DKK 377 M) advanced biofuel project with norwegian-swedish joint venture Silva Green Fuel in licensing deal”, [Online]. Available: https://steeperenergy.com/2017/12/15/steeper-energy-announces-eur-50-6-m-dkk-377-m-advanced-

biofuel-project-with-norwegian-swedish-joint-venture-silva-green-fuel-in-licensing-deal/ Retrieved: 2018-11-14

[87]: Statkraft, ”Silva Green Fuel”, [Online]. Available: https://www.statkraft.com/about-statkraft/Projects/norway/silva-green-fuel/ Retrieved: 2018-11-14

[88]: Fortum, ”Fortum Sustainability Report 2017”, 2018. [Online]. Available: https://www.fortum.com/sites/g/files/rkxjap146/files/documents/fortum_sustainability_2017.pdf Retrieved: 2018-11-14

[89]: BTG-BTL, ”Newsletter November 2017”, [Online]. Available: https://www.btg-btl.com/nieuwsbrieven/2017/november/en Retrieved 2018-11-14

[90]: A. Ernsting and R. Smolker, ”Dead end road: the false promise of cellulosic biofuels”, Biofuelwatch, United Kingdom, 2018. [Online]. Available: http://www.biofuelwatch.org.uk/wp-content/uploads/Cellulosic-biofuels-report-low-resolution.pdf Retrieved: 2018-11-14

[91]: Sunpine, ”Sunpine”, [Online]. Available: https://www.sunpine.se/ Retrieved: 2018-11-14

[92]: Ensyn, ”Cote Nord Project”, [Online]. Available: http://www.ensyn.com/quebec.html Retrieved: 2018-11-14

[93]: Ensyn, ”Aracruz Project”, [Online]. Available: http://www.ensyn.com/brazil.html Retrieved: 2018-11-14

[94]: Ensyn, ”Georgia Project”, [Online]. Available: http://www.ensyn.com/georgia.html Retrieved: 2018-11-14

[95]: Setra, ”Preem och Setra samarbetar kring förnybara drivmedel”, [Online]. Available: https://www.setragroup.com/sv/press/pressmeddelanden/2018/preem-och-setra-samarbetar-kring-fornybara-drivmedel/ Retrieved: 2018-11-14

[96]: Preem, ”Preem och RenFuel skapar världens första ligninanläggning för biodrivmedel”, [Online]. Available: http://www.mynewsdesk.com/se/preem/pressreleases/preem-och-renfuel-skapar-vaerldens-foersta-ligninanlaeggning-foer-biodrivmedel-2517569 Retrieved: 2018-11-14

[97]: Biozin, ”Samarbeidsavtale om produktion av biodrivstoff”, [Online]. Available: http://biozin.no/#presse Retrieved: 2018-11-14

[98]: Suncarbon, ”Technology”, [Online]. Available: https://www.suncarbon.se/technology/ Retrieved: 2018-11-14

[99] Verbio, ”Verbio acquires cellulose ethanol plant from du Pont in Nevada/Iowa, USA”, [Online], Available: https://www.verbio.de/en/investor-relations/news-publications/ad-hoc-announcements/verbio-acquires-cellulose-ethanol-plant-from-dupont-in-nevadaiowa-usa/ Retrieved 2018-12-07

[100] Preem, ”Preem och norska Biozin i samarbete om mer förnybara drivmedel, [Online], Available: http://news.cision.com/se/preem-ab/r/preem-och-norska-biozin-i-samarbete-om-mer-fornybara-drivmedel,c2689963 /Retrieved 2018-12-07

[101] Press release from Swedish government on Novemer 15, 2018, https://www.regeringen.se/pressmeddelanden/2018/11/okade-hallbarhetskrav-for-biodrivmedel-och-flytande-biobranslen/ /Retrieved 18-11-19

[102] © OECD/IEA Technology Roadmap – Delivering Sustainable Bioenergy, 2017, IEA Publishing. Licence: www.iea.org/t&c

[103] SET Plan Implementation Plan, Action 8: Bioenergy and Renwable Fuels for Sustainable Transport, June 2018

[104] Personal communication with Henrik Rådberg and Mattias Backmark, Preem, Sweden; Lars Waldheim, Waldheim Consulting, Sweden; Tomas Ekbom, Svebio, Sweden; Dina Bacovsky, Bioenergy 2020+, Austria.

APPENDIX A GLOBAL BIOFUEL PRODUCTION VOLUMES

Table A1 Global production of biofuels 2017 on country level, based on data from the Renewables 21 network [6].

	Ethanol GWh/a	Biodiesel (FAME) GWh/a	Biodiesel (HVO) GWh/a	Ethanol million litres/a	Biodiesel (FAME) million litres/a	Biodiesel (HVO) million litres/a
United States	354 449	55 798	16 048	59 979	6 028	1 700
Brazil	168 635	39 719	0	28 536	4 291	0
Germany	5 487	32 229	0	928	3 482	0
Argentina	6 530	30 380	0	1 105	3 282	0
China	19 572	9 669	0	3 312	1 045	0
France	5 830	21 486	0	987	2 321	0
Thailand	8 835	12 892	0	1 495	1 393	0
Indonesia	343	23 098	0	58	2 495	0
Canada	10 064	4 297	0	1 703	464	0
Netherlands	2 058	3 703	12 272	348	400	1 300
Spain	2 743	12 355	0	464	1 335	0
Poland	1 372	9 132	0	232	987	0
Singapore	686	0	12 461	116	0	1 320
India	4 801	1 611	0	812	174	0
Colombia	2 058	5 372	0	348	580	0
EU-28 rest	6 859	30 138	20 768	1 161	3 256	2 200
World rest	23 137	0	0	3 915	0	0
Total	**623 458**	**284 171**	**61 360**	**105 500**	**30 700**	**6 500**

Table A2 European production of biofuel 2016, based on data from United States Department of Agriculture and the European Biodiesel Board [5, 7].

	Ethanol GWh/a	Biodiesel GWh/a	Ethanol million litres/a	Biodiesel million litres/a
Germany	5 525	31 453	935	3 398
France	5 833	17 754	987	1 918
Netherlands	1 891	14 481	320	1 564
Spain	1 938	11 520	328	1 245
Poland	1 418	8 121	240	877
UK	3 900	2 742	660	296
Hungary	3 487	782	590	84
Belgium	3 368	4 785	570	517
Austria	1 324	3 148	224	340
Denmark/Sweden		4 389		474
Finland		4 462		482
Italy		5 244		567
Portugal		2 825		305
EU-28 rest	1 613	8 976	273	970
Total	**30 298**	**120 683**	**5 127**	**13 038**

It should be noted that the production figures from the different sources differs considerably. This is clearly seen when comparing the European production shown in the tables. Although the data are from trustable sources, total European figures differs with approximately 20%.

APPENDIX B VALUE CHAINS

THERMOCHEMICAL VALUE CHAINS

Thermochemical conversion into advanced biofuels are in the EIBI divided into three different value chains. These are described below. The diagrams come from the EIBI and/or SGAB. These are then commented and some adaptations for the purposes of this study are included, primarily in terms of potential feedstocks and products linked to the value chain.

In general, all value chains include as potential feedstock – besides lignocellulosic biomass – sustainable energy crops, waste and other types of residues.

VC1: Lignocellulosic feedstocks – Gasification – Liquid synthetic fuels/hydrocarbons for transportation

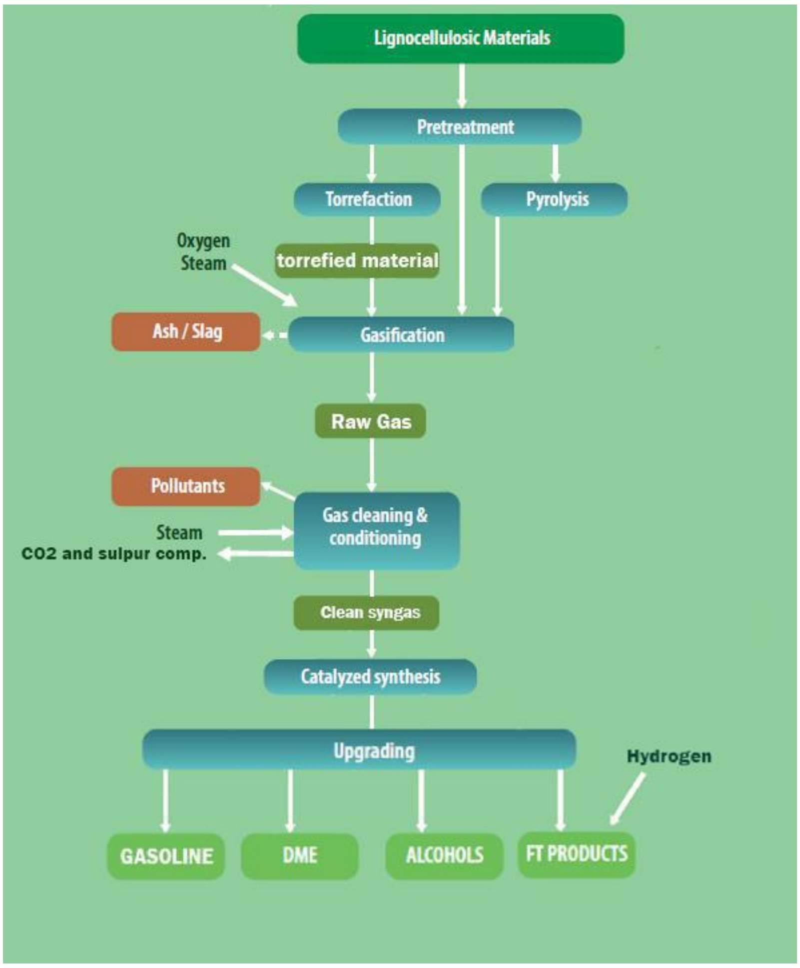

Figure B1 Flow chart of VC1 from ETIP Bioenergy [19]

As indicated in the diagram the value chain may also include the type of intermediate process steps that has been identified as a separate value chain (VC4).

The gasification technologies in focus for this VC include both entrained-flow gasifiers at high temperatures (1000-1500ºC) and bubbling and circulating fluidized bed gasifiers at lower temperature (700-950ºC).

Commercial plants of this type are expected to primarily be very large-scale stand-alone plants.

The VC implies high flexibility in both raw materials used and in products produced. However, the full value chain is most efficient with respect to biofuel energy yield for the production of biofuels close to the syngas components, i.e. methanol and DME.

VC 2 – Lignocellulosic feedstocks – Gasification – Biomethane (for transportation)

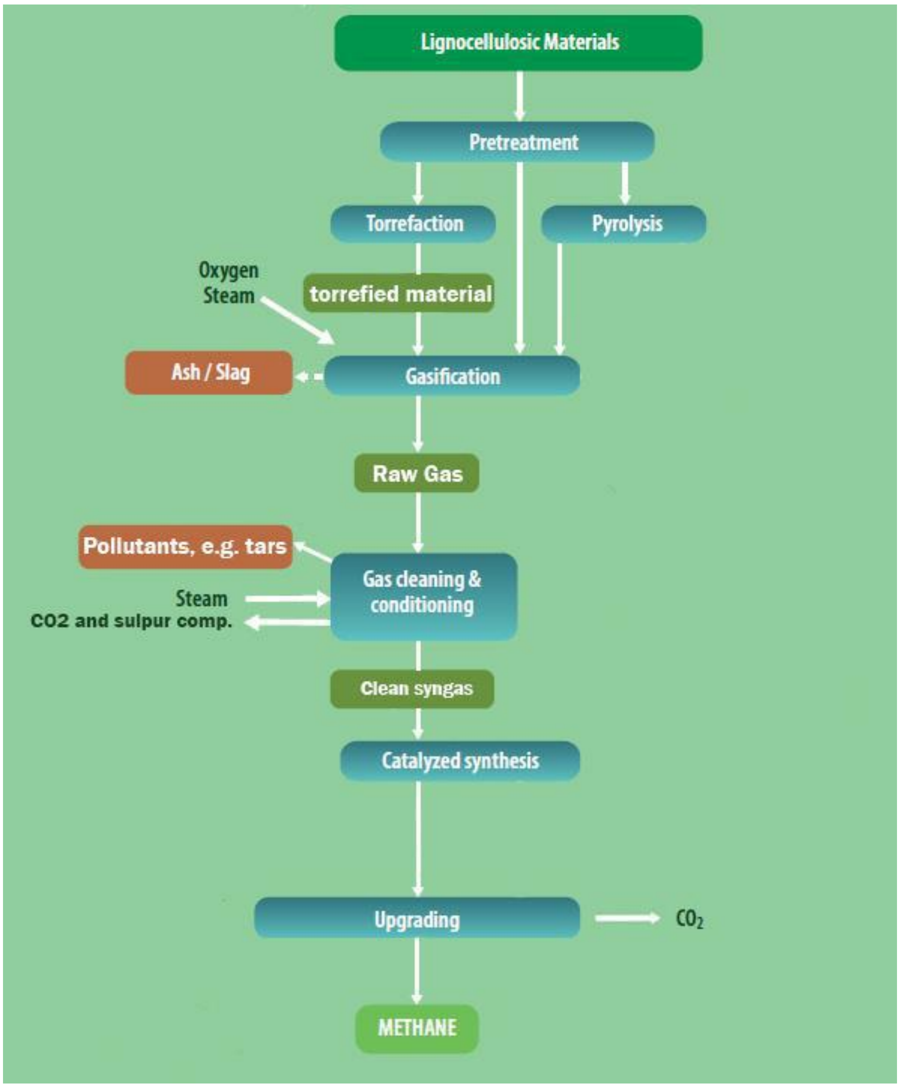

Figure B2 Flow chart of VC2 from ETIP Bioenergy [19]

As indicated in the diagram the value chain may also include the type of intermediate process steps that has been identified as a separate value chain (VC4).

The primary gasification technology this VC is bubbling and circulating fluidized bed gasifiers at lower temperature (700-950ºC), for which the raw gas is comparably rich in methane. This technology is also suitable for slightly smaller-scale plants and may be integrated with fluidized-bed heat boilers.

The value chain as it is described in the EIBI is directly identified based on bio-methane as final product, and has, thus, very low flexibility on the product side. Plants that include further processing into liquid fuels (e.g. methanol) are included in VC1.

VC 4 – Lignocellulosic feedstocks – Other thermochemical processes – Intermediates for upgrading into transport fuels

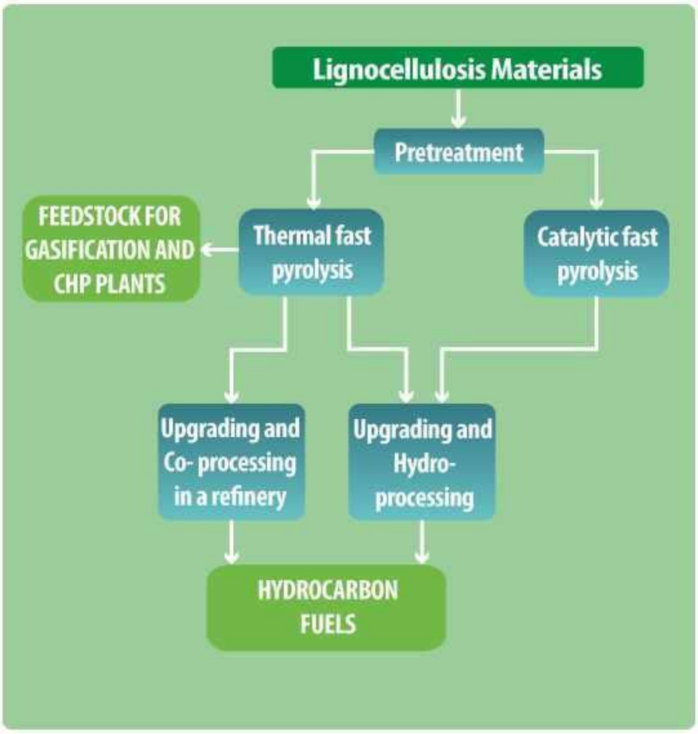

Figure B3 Flow chart of VC4 from ETIP Bioenergy [19]

The production of intermediate bioenergy carriers is motivated by allowing easier centralizing of large-scale final biofuel processing plants, through intermediate smaller-scale pre-processing units that increase the energy density, and thus logistics and transportation costs, of the feedstock for these large-scale plants.

May be included into several of the other VC, but has during the recent few years been increasingly in focus as a means of increasing the feedstock base for HVO production. Conversion technologies in focus include for instance fast pyrolysis, catalytic pyrolysis, and hydrothermal liquefaction.

This is an intermediate step, whose development is driven by the need for increasing flexibility on both the raw material and the product side.

BIOCHEMICAL VALUE CHAINS

Biochemical conversion of "advanced" biomass into biofuels are in the EIBI value chains divided into two different value chains. These are described below. The diagram below originates from the SGAB reports and includes both value chains. This is commented and some adaptations for the purposes of this study are included, primarily in terms of potential feedstocks and products linked to the value chain.

In general, all value chains include as potential feedstock – besides lignocellulosic biomass – sustainable energy crops, waste and other types of residues.

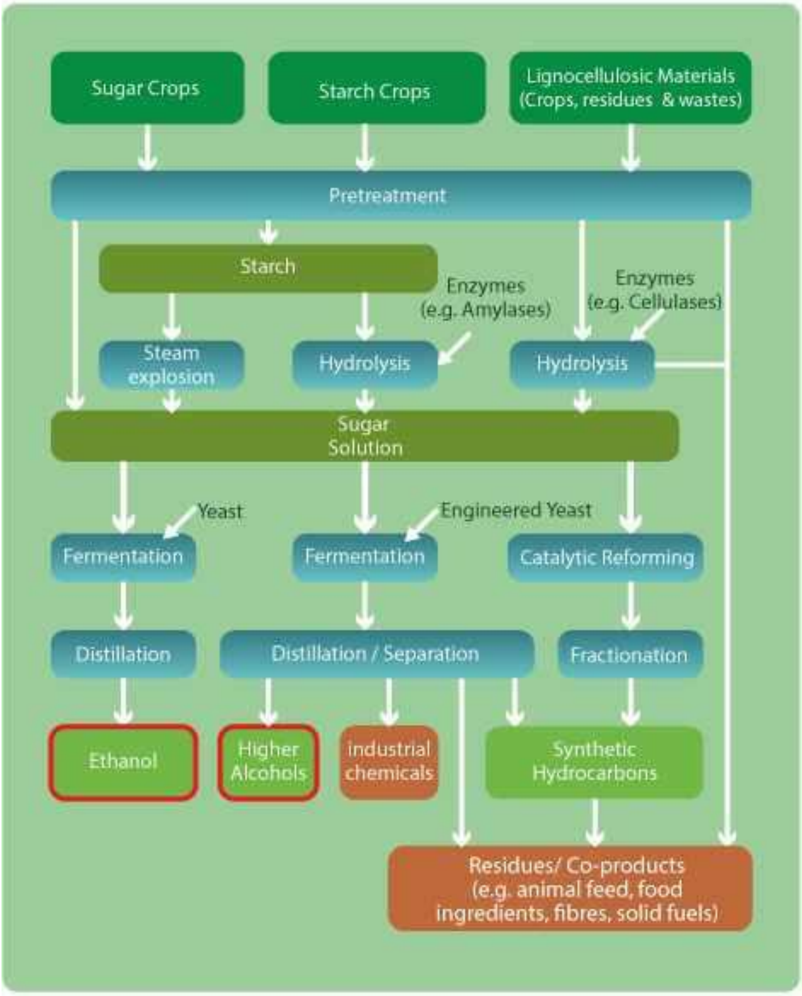

Figure B4 Flow chart of VC5 (left-hand side) and VC6 (right-hand side) from ETIP Bioenergy [19]

VC 5 – Lignocellulosic feedstocks and sustainable energy crops – Fermentation – Ethanol and higher alcohols as blend-ins (for gasoline market) and E85

VC5 is, as conventional ethanol production, based on fermentation technologies. However, or lignocellulosic feedstock novel fermentation technologies for fermenting both the C6 sugars of the cellulose and the C5 sugars of the hemicellulose are needed and recently developed. These technologies which require both pretreatment technologies, novel enzymes, as well as engineered yeasts. There are a number of technology variants that have in principal reached commercial status.

VC 6 – Lignocellulosic feedstocks and sustainable energy crops – Biological and/or chemical processes – Synthetic fuels/hydrocarbons for transportation

Include other biological and/or chemical processes such as microbial fermentation into another class of compounds (not alcohols) and different forms of catalytic conversions to fuel products that are suitable as drop-in fuels. Pretreatment steps converting the lignocellulosic feedstock into sugars are the same as in VC5.

There are currently no planned large-scale plans based on this value chain.

OLEOCHEMICAL VALUE CHAINS

VCX– Fatty acid containing materials – Hydrotreating – Diesel, naptha and biojets (synthetic hydrocarbons)

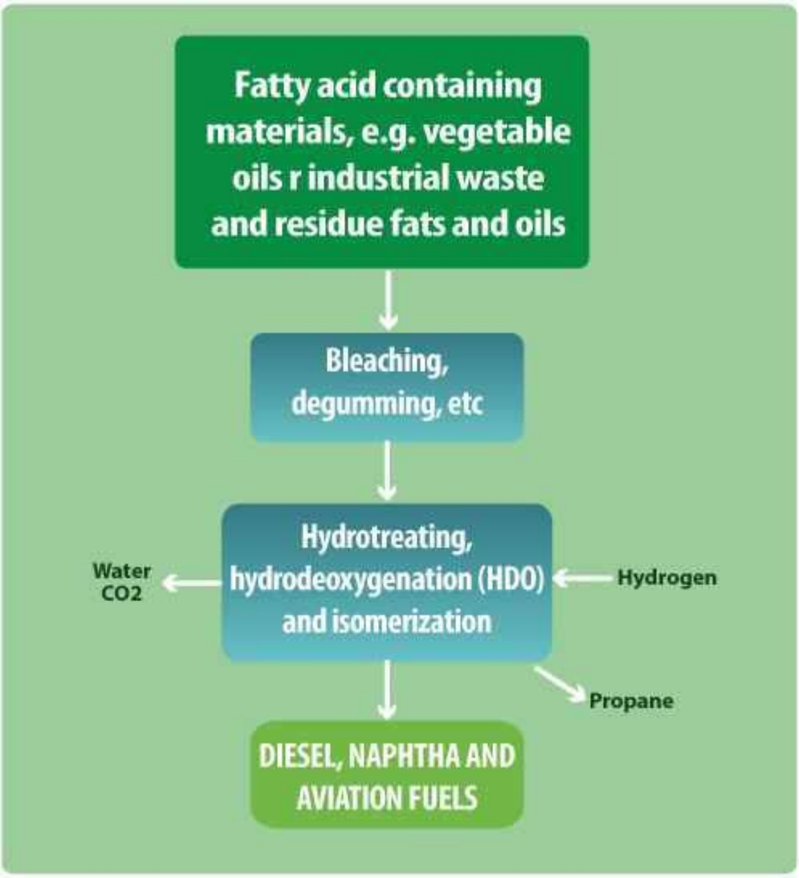

Figure B5 Flow chart of the value chain for HVO from SGAB [36]

The feedstock of this VC is, according to the diagram above, limited to fatty acid containing material. However, by development of and integration with pretreatment steps described under VC4, the flexibility of the feedstock base may increase.

Production plants may be stand-alone greenfield plants; based on conversion of fossil refineries or on co-processing with fossil feedstocks. The potential benefits of and process solutions for integration of the HVO production into the refinery then depend on the feedstock quality and pretreatment processes used.

Production of HVO increases the demand for hydrogen in the refinery process, compared to fossil feedstock.

The flexibility on the product side is large, since the conversion processes are similar to (or integrated with) those of a fossil refinery.

APPENDIX C PLANT DATA FOR ADVANCED BIOFUEL PRODUCTION

Table C1: Existing and operational gasification plants

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m3)	Produced 2017	Investment/economy	References
Enerkem (Canada)	Enerkem Edmonton	Edmonton, Canada	2015	Operational	MSW	Ethanol[1]	225 (38 020)	- [2]	120 MCAD [3]	22, 23,36,37,38

[1] Initially designed for methanol production. Ethanol conversion unit added September 2017.
[2] No production data available. However, ethanol production did not start until September 2017. As of February 2018, it had not yet reached full production (Edmonton Journal: https://edmontonjournal.com/business/local-business/five-minutes-from-trash-to-ethanol-edmontons-long-delayed-enerkem-plant-explained). Ethanol production in 2017 is likely to have been very low.
[3] Excluding waste separation unit [36]

Table C 2: Existing and operational large scale fermentation plants. Grey rows include more general, not plant specific data.

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m3)	Produced 2017	Investment/economy	References
Borregaard AS (Norway)	ChemCell Ethanol	Sarpsborg, Norway	1938	Operational	Sulphite liquor	Ethanol	118 (20 000)	-		42,43
Adity Abirla (Sweden)	Domsjö fabriker	Örnsköldsvik, Sweden	1909	Operational	Sulphite liquor	Ethanol	105 (17 740)	122[1]		44,45
Poet-DSM (USA)	Project Liberty (Poet-DSM)	Emmetsburg, USA	2014	Operational	Corn-stover	Ethanol	558 (94 500)	< 127 [2,3]	250 MUSD	22,23,62
GranBio (Brazil)	GranBio Bioflex 1	Sao Miguel, Brazil	2014	Operational	Sugar cane bagasse and straw	Ethanol	472 (80 000)	29	SGAB[4]	22,23,64
Raizen Energia (Brazil)	Raizen Energia	Costa Pinto, Brazil	2015	Operational	Bagasse	Ethanol	249 (42 200)	88	SGAB[4]	22,23,64
Cane Technology Center (Brazil)	Cane Technology Center	Sao Manuel, Brazil	2012	Operational	Bagasse	Ethanol	18 (3 040)	-	38,5 MUSD	22,65
Longlive Biotech (China)	Longlive biotech	Yucheng, China	2012	Operational	Corn cob	Ethanol	446 (75 600)	-		22,26

Henan Tianguan Group (China)	Henan Zhenping	Zhenping, China	2009	Operational	Wheat/corn stover	Ethanol	75 (12 670)	-		22,26
Henan Tianguan Group (China)	Henan Nanyang	Nanyang, China	2011	Operational	Crop residues	Ethanol	225 (38 020)	-		22,26
US	Aggregated in conv plants	-	-	Operational	Corn kernel fibre	Ethanol	690 (116 800)	< 127[2]		26
Nordic countries	Aggregated in conv plants			Operational	Food waste	Ethanol	About 150 GWh[5]			

[1] Sustainability report 2017.
[2] Based on renewable identification numbers (RINs) reported by the US EPS 2017. Includes all cellulosic ethanol production in the US.
[3] Production at Project Liberty has been held back by pre-treatment issues. In November 2017 a new pre-treatment system was installed, working at 80 % uptime (http://poetdsm.com/pr/poet-dsm-achieves-cellulosic-biofuel-breakthrough)
[4] Economic data for this plant is available in the SGAB cost report, but we have not been able to extract an unambigous figure, and therefore we refer to the original data in the reference [36].
[5] This estimate is only included to give an order of magnitude, data is uncertain.

Table C3: Existing and operational large-scale plants for hydrotreatment of fatty acid feedstocks

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m3)	Produced 2017	Investment/economy	References
Neste (Finland)	Neste Porvoo 1	Porvoo, Finland	2007	Operational	Various FOG[1]	HVO	2435 (254 780)	2386	1 BSEK	23, 24, 46, 66
Neste (Finland)	Neste Porvoo 2	Porvoo, Finland	2009	Operational	Various FOG[1]	HVO	2435 (254 780)	2386	1 BSEK	23, 24, 46, 66
Neste (Singapore)	Neste Singapore	Singapore	2010	Operational	Various FOG[1]	HVO	13390 (1 401 270)	13122	3-15 EUR/MWh[4]	23, 46, 66
Neste (Netherlands)	Neste Rotterdam	Rotterdam, Netherlands	2011	Operational	Various FOG[1]	HVO	13390 (1 401 270)	13122	3-15 EUR/MWh[4]	23, 46, 66
UPM (Finland)	UPM Lappeenranta	Lappeenranta, Finland	2015	Operational	Crude tall oil	HVO	1217 (127 390)	Reached design capacity	175 MEUR	23, 31, 67
Eni (Italy)	ENI Venice	Venice, Italy	2014	Operational	15 % UCO, 85 % vegetable oils	HVO	3287-4260 (343 950-445 860)	2921	-	33,68,69
Diamond Green Diesel (USA)	Diamond Green Diesel	Norco, USA	2013	Operational	UCO, animal fats, inedible corn oil	HVO	9933 (1 039 500)	-	3-15 EUR/MWh[4]	23,25,70

Renewable Energy Group (USA)	REG Geismar	Geismar, USA	2010	Operational	Crude, High FFA and Refined Oils and Fats [2]	HVO	2709 (283 500)	-	3-15 EUR/MWh[4]	28,71
Preem (Sweden)	Preem Göteborg	Göteborg, Sweden	2010	Operational	Crude-tall diesel, animal fats, rapeseed oil [3]	HVO	2102 (220 000; 320 000 from 2019)	FEED: 163 000 m^3	250 MSEK 2010; 350 MSEK 2015; 500 MSEK 2018[5]	32,47,72
WorldEnergy (USA)	AltAir Plant	Paramount, USA	2016	Operational	Inedible agricultural fats and oils	HVO (jet-quality)	1445 (151 200)	-	3-15 EUR/MWh[4]	25,28,73
Cepsa (Spain)	Cepsa Refineries	Spain		Operational		HVO	730 (76 400)		-	23,25
Repsol (Spain)	Repsol Refineries	Spain		Operational		HVO	730 (76 400)		-	23,25
Sinopec (China)	Sinopec	China	?	Operational	FOG	HVO (jet-quality)	243 (25 480)	-	3-15 EUR/MWh[4]	25
Total (France)	Total La Mede	La Mede, France	2018	Start-up	Vegetable oils, used/residual	HVO	6086 (636 490)	n/a	3-15 EUR/MWh[4]	25, 74

					oils, animal fats					

[1] Aggregated feedstock mix for all Neste HVO-plants is: 76 % waste and residues (including PFAD), 24 % vegetable oils (Neste annual report 2017).

[2] FFA: Free fatty acids. Company annual report: http://www.annualreports.com/HostedData/AnnualReportArchive/r/NASDAQ_REGI_2016.pdf

[3] Mainly tall-diesel. No palm oil or PFAD: https://www.preem.se/om-preem/insikt-kunskap/gronare-drivmedel/satsning-pa-fornybar-diesel-ar-viktigare-an-nagonsin/

[4] Based on [36]. Assumptions: 8000 operating hours per year, 15 years economic lifetime, 10 % real interest[4]

[5] Original investment 2010 250 MSEK for capacity of 100 000 m3; Additional investment 2015 350 MSEK to double capacity; 500 MSEK are now (2018) being invested in production of H2 necessary to increase biobased feedstock in refinery. This will increase HVO production capacity to 320 000 m3 from 2019 [104]

Table C4: Planned large-scale gasification plants

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m3)	Produced 2017	Investment/economy	References
RedRock (USA)	RedRock Lakeview	Lakeview, USA	?	Under construction	Forest residues	Diesel-type fuel	576 (57 000)	n/a	200 MUSD	22,50,75
Fulcrum (USA)	Fulcrum Sierra	Nevada, USA	2020	Under construction	MSW	Syncrude	421 [1] (36 960)	n/a	280 MUSD	51,75,76
Enerkem (Canada)	Enerkem Vanerco	Varennes, Canada	2019	Planned	Mixed waste	Ethanol (methanol)	225 (38 020)	n/a	-	22,23,48
Enerkem (Netherlands)	Enerkem Rotterdam[2]	Rotterdam, Netherlands	?	Planned	Mixed waste	Methanol	1228 (277 780)	n/a	200 MEUR	29,48,49
Aemetis/LanzaTech (USA)	Aemetis California	Riverbank, USA	2019	Planned	Biomass	Ethanol	262 (44 360)	n/a	158 MUSD	35,52
Kaidi (Finland)	Kaidi Kemi	Kemi, Finland	2019	Planned	Forest residues	FT-diesel	2403 (239 520)	n/a	1 BEUR	22,77
BioTfueL (France)	BioTfueL commercial	France	2020:s	Planned	Various biomass	FT-diesel	2403 (239 520)	n/a	-	23,53

[1] Assuming LHV 38.2 MJ/l (heavy fuel oil)
[2] This plant will produce methanol for use in chemicals production

Table C5: Idle large scale advanced fermentation plants

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m3)	Produced 2017	Investment/economy	References
BetaRenewables (Italy)	Betarenewables Crescentino	Crescentino, Italy	2013	Idle	Straw, arundo	Ethanol	299 (50 700)	n/a	225 MEUR	22,39,78
SynataBio (USA)	SynataBio Hugoton	Hugoton, USA	2014	Idle	Corn stover	Ethanol	558 (94 500)	n/a	SGAB[1]	22,23,26,40
INEOS Bio (USA)	INEOS Bio	Vero Beach, USA	2012	Idle	Vegetative and wood waste	Ethanol	179 (30 240)	n/a	132 MUSD	22,26
DuPont (USA)	DuPont Nevada	Nevada, USA	2016	Idle	Corn stover	Ethanol	670 (113 400)	n/a	225 MUSD	22,23,26,41

[1] Economic data for this plant is available in the SGAB cost report, but we have not been able to extract an unambigous figure, and therefore we refer to the original data in the reference [36].

Table C6: Planned large scale advanced fermentation plants. Grey rows include more general, not plant specific data.

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m3)	Produced 2017	Investment/economy	References
Fiberight (USA)	Fiberight Hampden	Hampden, USA	2019	Under construction	MSW	Ethanol	134 (22 680)	n/a		22,26,55,56
COFCO (China)	COFCO Zhaodong	Zhaodong, China	2018	Planned	Various lignocellulosics	Ethanol	374 (63 370)	n/a		22,26,27
Clariant (Romania)	Clariant Romania	Romania	2020	Under construction	Agricultural residue	Ethanol	374 (63 370)	n/a		22,51,54
Clariant+Enviral (Slovakia)	Clariant Slovakia	Slovakia	2020	Planned	Agricultural residue	Ethanol	374 (63 370)	n/a		22,27
St1 (Norway)	Cellunolix NO	Honefoss, Norway	2020	Planned	Wood	Ethanol	295 (50 000)	n/a		23,27,57
St1 (Finland)	Cellunolix FI1	Finland	2020	Planned	Wood	Ethanol	295 (50 000)	n/a		23,27,57
St1 (Finland)	Cellunolix FI2	Finland	2020	Planned	Wood	Ethanol	295 (50 000)	n/a		23,27,57

Kanteleen Vaimo (Finland)	NordFuel Refinery	Finland	2022	Planned	Wood	Ethanol	487 (82 380)	n/a	150 MEUR	57,79
Henan Tianguan Group (China)	Henan Nanyang 2	Nanyang, China	?	Planned	Crop residues	Ethanol	1 116 (189 000)	n/a		26
New Energy Blue (USA)	New Energy Spirit, USA	Jamestown, USA	2021	Planned	Crop residue	Ethanol	357 (60 480)	n/a		80
BetaRenewables (Slovakia)	Beta Renewables Energochemica	Strazske, Slovakia	2017	Under construction (possibly on hold)	Agricultural residues	Ethanol	412 (69 710)	n/a		22,26,27
BetaRenewables (USA)	Beta Renewables Alpha	Clinton, USA	2018	Under construction (possibly on hold)	Energy grasses	Ethanol	446 (75 600)	n/a		22,26,27
BetaRenewables (China)	Beta Renewables Fujiang	Fujiang, China	2018	Planned (possibly on hold)	Wheat straw, corn stover	Ethanol	670 (113 400)	n/a		22,26
India - unspecified	12 plants			Planned	Various cellulosic	Ethanol	About 60 GWh/year each			

Table C7: Planned large-scale plants for hydrotreatment of fatty acid feedstocks

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m3)	Produced 2017	Investment/ economy	References
Eni (Italy)	Eni Gela	Gela, Italy	2018	Planned	Vegetable oils	HVO	7304 (764 330)	n/a	-	33,68
Eni (Italy)	Eni Venice Expansion	Venice, Italy	2021	Planned	Vegetable oils, UCO, animal fats	HVO	852-1826 (89 170-191 080)	n/a	-	33,68
St1 (Sweden)	St1 Göteborg	Göteborg, Sweden	2021	Planned	Crude tall-diesel, other oils and fats	HVO	2435 (254 780)	n/a	400 MSEK	24, 83, 84
Preem (Sweden)	Preem Expansion	Göteborg+Lysekil, Sweden	2023	Planned	Waste FOG/ bio-oils from forestry residues	Ren. Diesel, gasoline, jet-fuel	10 914 (1 080 000)	n/a	1500 MSEK	24, 32, 34
Neste (Singapore)	Neste Singapore Expansion	Singapore	2022	Planned	Various FOG[1]	HVO	14607 (1 528 660)	n/a	-	25,66
SG Preston (USA)	SGP South Point	South Point, USA	2020	Planned	FOG	HVO	4334 (453 600)	n/a	3-15 EUR/MWh[2]	26,28,81

Colabitoil (Sweden)	Colabitoil	Norrsundet, Sweden	2021	Planned	FOG	HVO	6086 (636 940)	n/a	4 BSEK	57,82
Petrobras (Brazil)	Petrobras	Brazil	-	Planned	-	HVO	2800 (292 990)	n/a	3-15 EUR/MWh[2]	25
Petrixo (UAE)	Petrixo	UAE	-	Planned	-	HVO	4869 (509 550)	n/a	3-15 EUR/MWh[2]	25
Emerald Biofuels (USA)	Emerald Biofuels	Louisiana, USA	-	Planned	Non-edible oils	HVO	3973 (415 800)	n/a	3-15 EUR/MWh[2]	25

[1] Aggregated feedstock mix for all *current* Neste HVO-plants is: 76 % waste and residues (including PFAD), 24 % vegetable oils (Neste annual report 2017).
[2] Based on [36]. Assumptions: 8000 operating hours per year, 15 years economic lifetime, 10 % real interest.

Table C8: Planned large-scale plants for hydrotreatment of up-graded lignocellulosic materials

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m3)	Produced 2017	Investment/economy	Comments
SCA (Sweden)	SCA Östrand	Östrand, Sweden	2024	Planned	Wood and black liquor	Renewable diesel+gasoline	3631 (359 280)	n/a	3 BSEK	42,85
Södra, Statkraft (2023)	Silva Green Fuels	Norway	2023	Planned	Wood residues	Renewable diesel	1011-1516 (100 000-150 000)	n/a		57, 86, 87
UPM (Finland)	UPM Kotka	Kotka, Finland	2020	Planned	E.g. solid wood biomass	Renewable fuels	6051 (598 800)	n/a		31

[1] Not specified further by UPM

Table C9: Plants for the production of intermediate bioenergy carriers for the production of transportation fuels

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m3)	Produced 2017	Investment/economy	Comments
Pretreatment of tall-oil										
Sunpine (Sweden)	Sunpine[3]	Piteå, Sweden	2010	Operational	Crude-tall oil	Crude-tall diesel	100 000 m^3	100 000 m^3	350 MSEK	91

Sunpine (Sweden)	Sunpine Expansion[3]	Piteå, Sweden	2020	Planned	Crude-tall oil	Crude tall-diesel	60 000 m^3	-	250 MSEK	91
SCA+St1 (Sweden)	SCA+St1 Tall-diesel [5]	Göteborg, Sweden	2021	Planned	Crude tall oil	Crude tall diesel	100 000 m^3	n/a	-	84
Fast pyrolysis										
Fortum (Finland)	Fortum Joensuu	Joensuu, Finland	2014	Operational	Forest residues	Crude bio-oil	264 (50 000)	59[1]	30 MEUR	22,23,75,88
BTG-BTL (Netherlands)	Empyro	Hengelo, Netherlands	2015	Operational	Wood residue	Crude bio-oil	106 (20 000)	Reached design capacity[2]		22,23,75,89
Ensyn (Canada)	Ensyn Refrew	Renfrew, Canada	2006	Operational	Forest residues	Crude bio-oil	59,9 (11 340)	33,9	19 MEUR	23,58,90
Ensyn (Canada)	Ensyn Cote-Nord	Port Cartier, Canada	2018/ 2019	Planned	Woody biomass	Crude bio-oil	209 (39 690)	n/a		22,92
Ensyn+Fibria (Brazil)	Ensyn Brazil	Aracruz, Brazil	?	Planned	Eucalyptus residues	Crude bio-oil	439 (83 600)	n/a		22,93
Ensyn (USA)	Ensyn Georgia	Dooley County, USA	?	Planned	Mill and forest residues	Crude bio-oil	399 (75 600)	n/a		94

Preem, Setra (Sweden)	Pyrocell plant [3]	Gävle, Sweden	2021	Planned	Sawdust	Pyrolysis oil	26,4 kton	n/a	300 MSEK	42,32,95
Hydropyrolysis and other types of thermal liquefaction										
Rottneros, Renfuel, Preem (Sweden)	Rottneros Renfuel [3]	Vallvik, Sweden	2021	Planned	Lignin (black liquor)	Lignin-oil	30 kton	n/a	500 MSEK	42,32,96
Bergene Holm, Sweden	Biozin [3]	Jordöya, Norway	2022	Planned	Wood	Bio-oil	5*120 Ml [6]	n/a	5*2.5B NOK [7]	57,32,97,24
Suncarbon (Sweden)	Suncarbon [4]	Sweden	2022	Planned	Lignin (black liquor)	Lignin-oil	50 kton	n/a		42, 98

[1] Company sustainability report (11,200 tonnes)

[2] According to a company newsletter (November 2017), design capacity in terms of production rate and uptime was reached towards the end of 2017. In October 2017, aggregated production (since start-up 2015) reached 20 Ml (nameplate capacity: 20 Ml/y). https://www.btg-btl.com/nieuwsbrieven/2017/november/en

[3] Plants developed as JV between Preem and other actors to be part of the supply chain for Preem renewable fuel expansion.

[4] Product destined for use as refinery feedstock

[5] JV between St1 and SCA to produce crude tall-diesel from pulping process residues, for further processing in St1 refineries.

[6] 5 plants with the same capacity are planned. Location and start-up year are for the first plant. Start-up years are not specified for the remaining four plants

APPENDIX D ADDITIONAL FIGURES

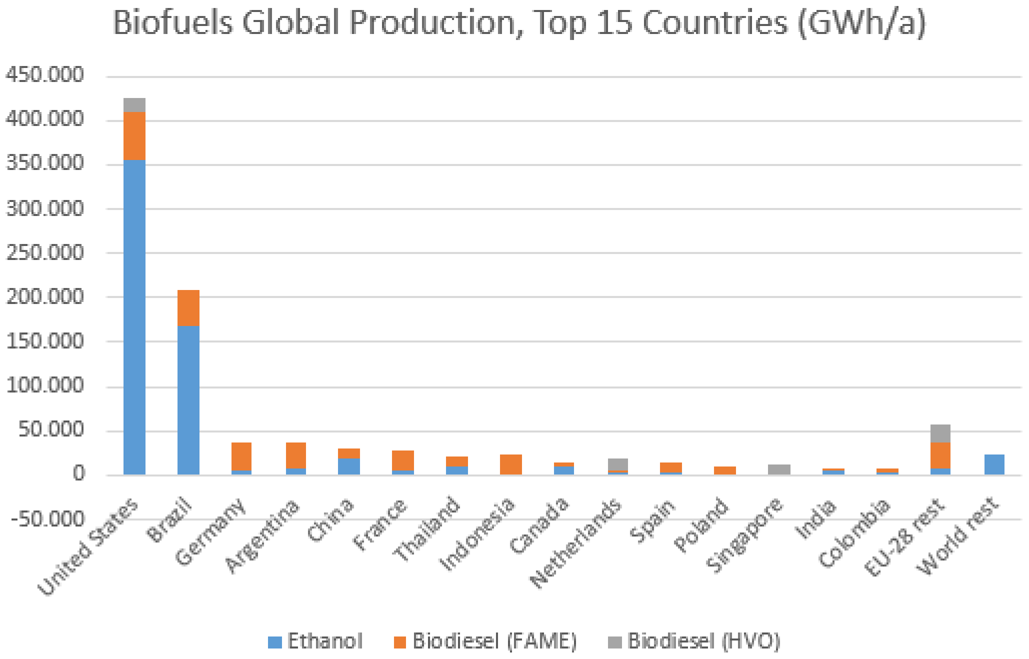

Figure D.1 Global production of biofuels 2017, top 15 countries. See also Appendix A for data [6].

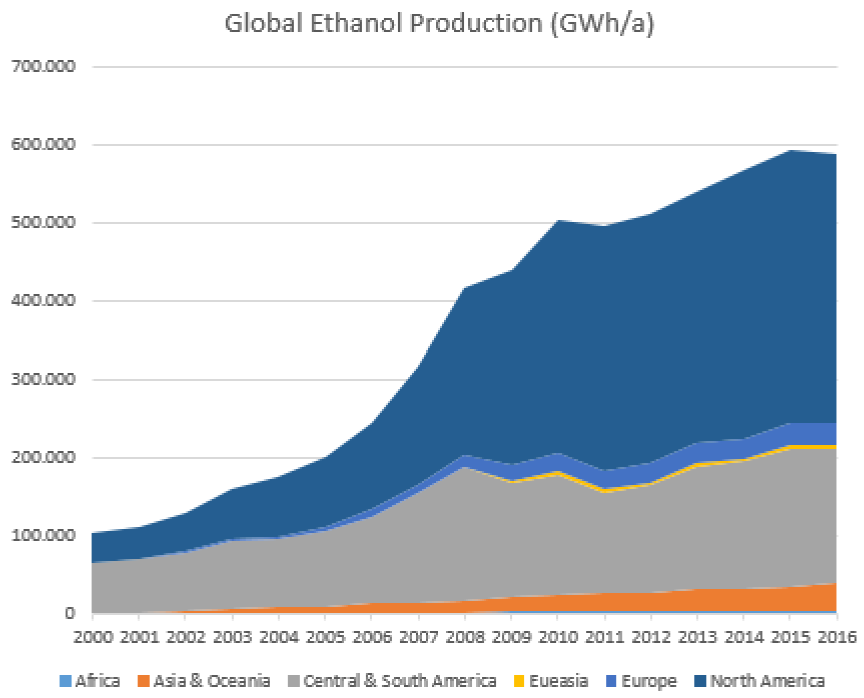

Figure D.2 Global ethanol production divided between producing regions (97 % of ethanol produced in Central & South America is produced in Brazil and 92 % of North American production takes place in the US). [4]

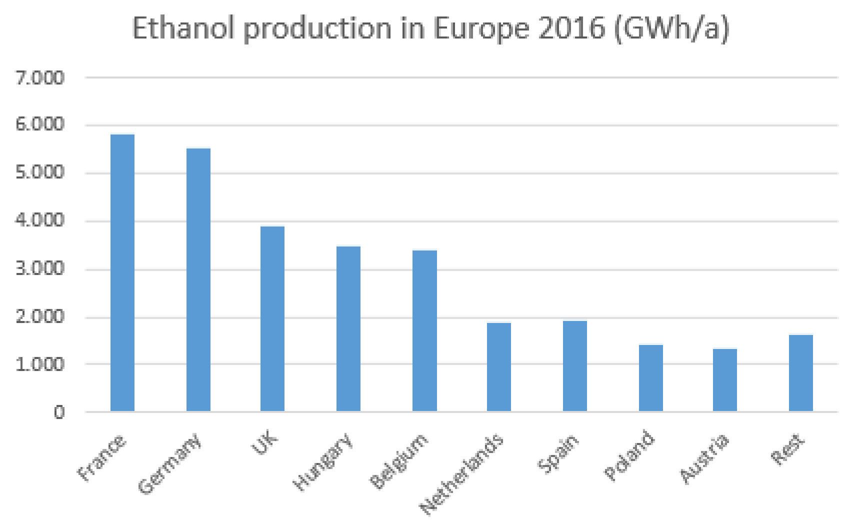

Figure D.3 European ethanol production specified between countries [7] See also Appendix A for data.

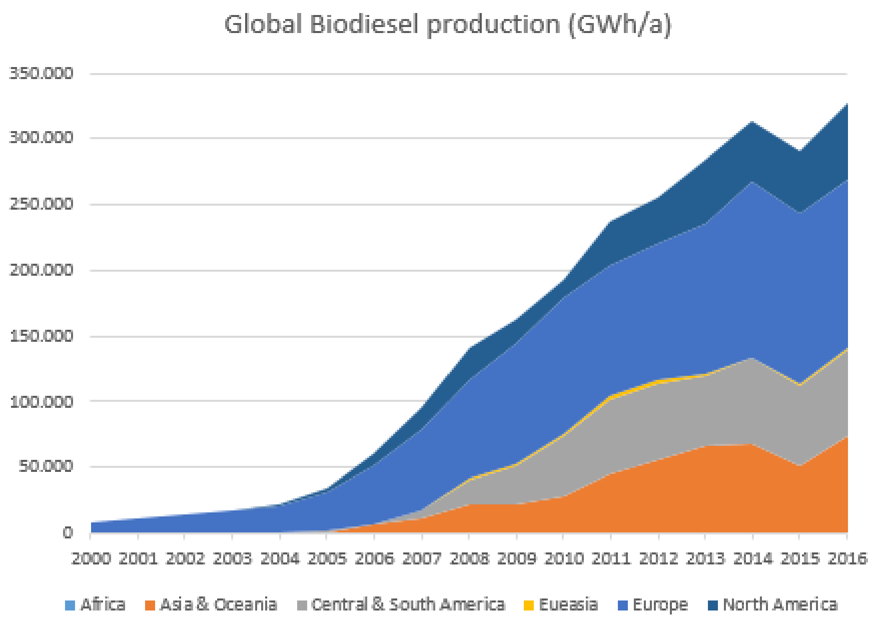

Figure D.4 Global biodiesel production divided between producing regions. [4]

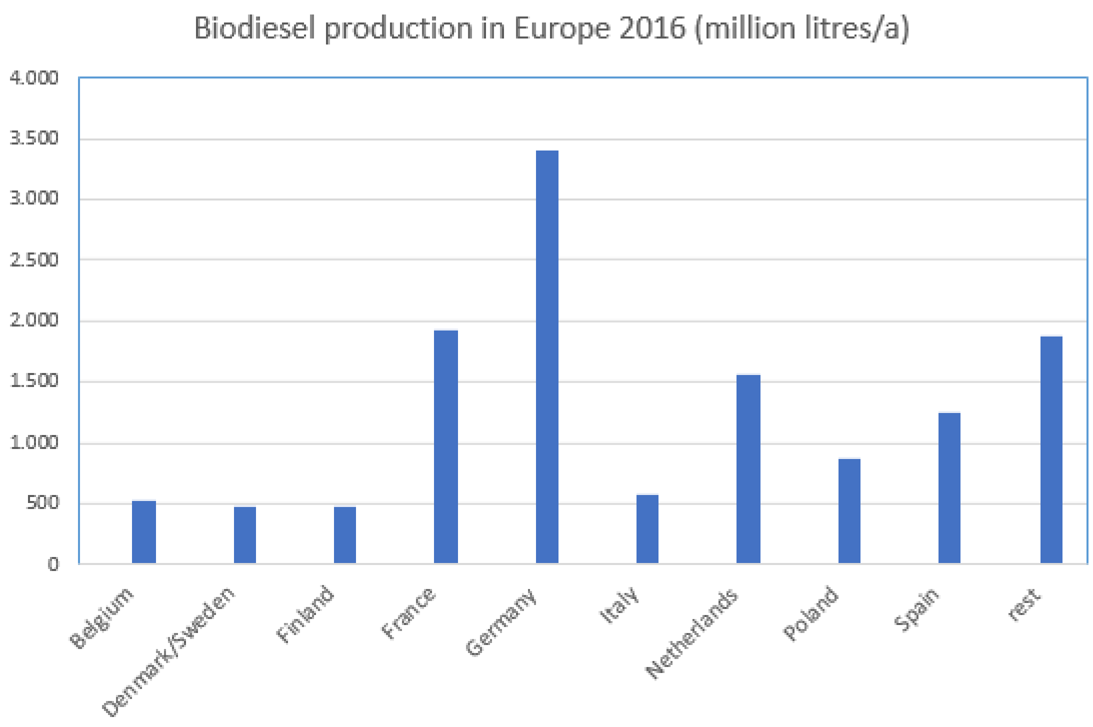

Figure D.5 European biodiesel production divided between main producing countries. [5]

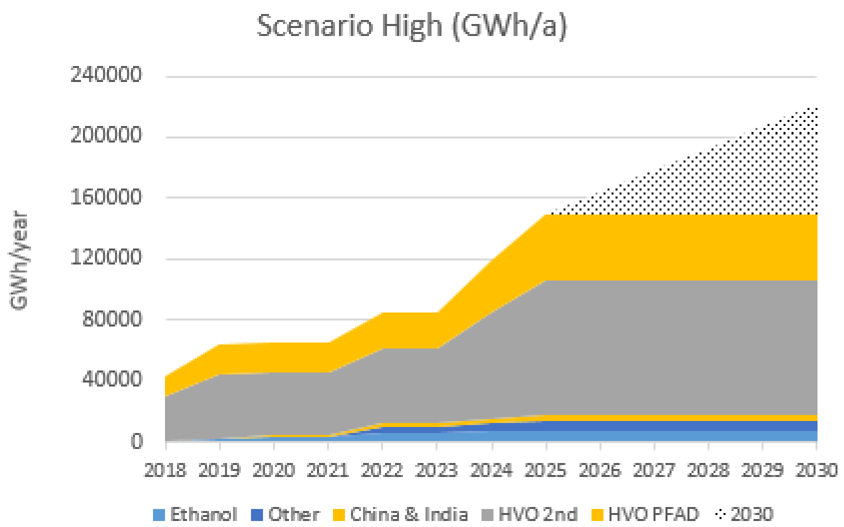

Figure D.7 Development of global advanced biofuel production, according to Scenario High. The dotted area represent a potential increase from the year 2025, with a continued development of plants at similar rates as before. This production is above the plant inventory and not linked to any specific plants.

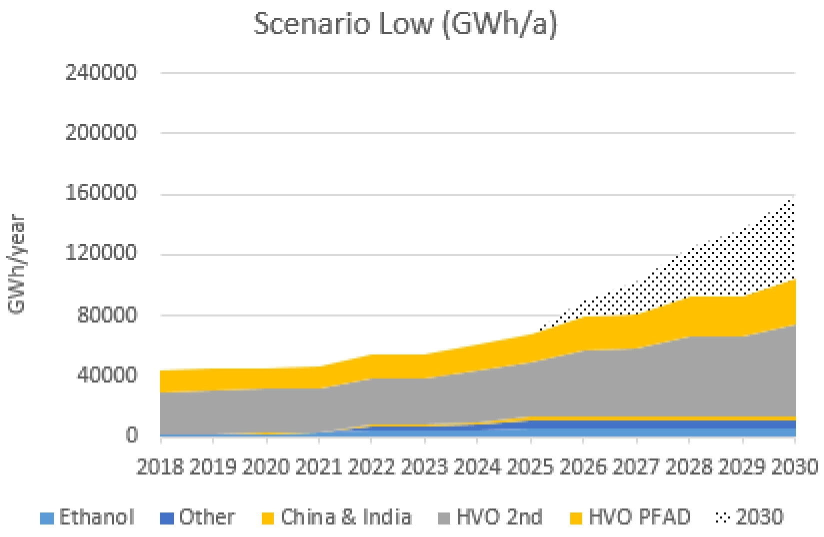

Figure D.8 Development of global advanced biofuel production, according to Scenario Low. The dotted area represent a potential increase from the year 2025, with a continued development of plants at similar rates as before. This production is in addition to the plant inventory and not linked to any specific plants.

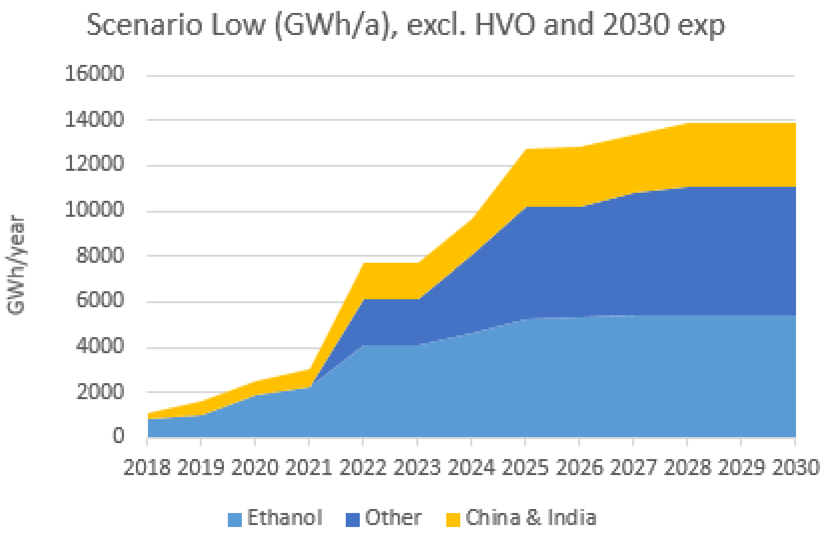

Figure D.9 Development of global production of advanced biofuels other than HVO, according to Scenario Low. In Scenario High total production in 2030 amounts to 18.1 TWh.

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