2019-05-06

Global production of bio-methane and synthetic fuels - overview

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EXECUTIVE SUMMARY

This study provides an overview of current and future global production of bio-methane and synthetic fuels for use in the transportation sector. The study is made by CIT Industriell Energi on assignment of the Norwegian environment agency. The report complements an earlier report that gives an overview of value chains for the production of liquid advanced biofuels. Together these two reports give a quite complete picture of potential renewable fuel production in the shorter (5-10 years) term. In addition, they describe the most relevant value chains for this time perspective and some of their more vital linkages.

The current report includes two very different groups of transport fuel value chains – partly bio-methane which is fairly well-established; partly synthetic fuels, which are currently on a much lower technology readiness level. It should be pointed out that there is no specific logic behind putting these two groups into the same report, other than that they were not included in the former report. Consequently, the scope and methodologies for each of the groups differ, and they are therefore summarized separately below.

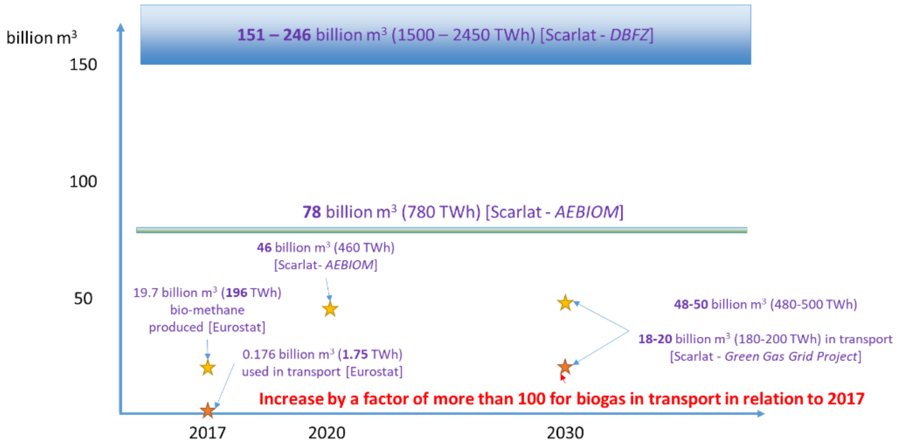
<u>Production of bio-methane for use in the transportation sector</u>

Production of bio-methane, currently as well as in the near future, is mainly based on the value chain of anaerobic digestion. This is a small-scale commercial biofuel conversion technology, meaning that there are a very large number of existing and planned plants worldwide. The application of biogas is versatile, ranging from heating only, combined heat and power generation to gas upgrade for injection in the gas grid or direct use as biofuel. Among European countries there are substantial differences with respect to policies regulating the use of biogas, a general trend towards more and more upgrade to bio-methane being noticeable. The other relevant value chain – biomass gasification for the production of bio-methane – has been successfully demonstrated at near-industrial scale but currently there are no tangible plans for large scale plants. Bio-methane via gasification in addition competes with other viable value chains producing liquid fuels – such as ethanol, methanol, dimethyl ether or FT-Diesel – that might be preferable with respect to infrastructural issues.

The potential for bio-methane production has been assessed in a number of studies, realistic estimates on a technical potential in the time frame of 2030 indicating about 50 billion m^3 (or 500 TWh) of bio-methane production in Europe being feasible (see figure below). Larger estimates often include biomass gasification and rely to a large extent on energy crops for anaerobic digestion that are cultivated via crop-rotation or sequential cropping. The latter concepts might lead to land use conflicts for food and feed production but have been shown to be able to actually improve soil properties (reduced erosion and improved soil carbon content) and increase crop yields (thus actually not leading to land use conflicts), given proper management and climatic conditions.

An estimate of bio-methane potential for gas grid injection of use as transport fuel for 2030 indicates about 18-20 billion m^3 of bio-methane being possible. On a European level, that could actually mean an increase of bio-methane as transport fuel by a factor of more than 100 compared

to 2017. For the Denmark, Sweden, Norway and Finland, a realistic bio-methane potential – again basically stemming from anaerobic digestion – in the range of 60 TWh has been identified.



Bio-methane potential in Europe within the timeframe up to 2030 (squares represent theoretical potential estimates, stars current (2017) respectively future realistic bio-methane potential).

Bio-methane from anaerobic digestion is an environmentally sound technology for valorizing local waste streams and there are a number of local transport applications (e.g. public transport or waste collection trucks) that are realized all over the world. There are in addition, a number of technology developments that may improve the prospects of bio-methane as a transport fuel. The most relevant technology is liquefaction of bio-methane that is becoming more and more viable even at the relative small scale of digestion plants (due to the given limited local feedstock potential). Once liquefied the bio-methane can be used as a fuel in heavy duty transports or for shipping. Technologies proposing further conversion of biogas from digestion to liquid fuels (e.g. Renovare Fuels) are however considered to be hardly feasible in the near future, due to the necessary economy of scale for such technologies, making them hardly feasible at biogas plant scales. However, there exist synergies between biogas from anaerobic digestion and the synthetic fuel value chain to bio-methane from hydrogen and carbon dioxide, as biogas from digestion basically is a mixture of methane and carbon dioxide. The carbon dioxide needs to be separated during an upgrade step to bio-methane and consequently represents a pure and low cost feedstock for synthetic fuel pathways. There even exist promising technologies (e.g. Electrochaea) that demonstrated the conversion of the carbon dioxide in raw biogas from digestion with extra hydrogen from renewable electricity via a bio-methanation, replacing the gas upgrade via CO_2 separation and boosting the bio-methane yield from anaerobic digestion.

Production of synthetic fuels

In the group of synthetic fuels, three different value chains are included in this report. Firstly, *electrofuels*, which are produced using electricity as main energy input for producing alcohols or hydrocarbons, together with CO_2. These are included in the definition of renewable liquid and gaseous fuels of non-biological origin, used in EU:s revised renewable energy directive (RED II), as long as the electricity used is derived from renewable sources. Secondly, two types of fossil waste-based fuels. Partly *fuels based on gases from waste treatment processes or flue gas of non-renewable origin*, such as steel mill flue gases, partly *fuels based on waste plastics and/or rubber*. These are included in the definition of recycled carbon fuels, used in the RED II.

These fuels are thus included in the RED II. From the directive it is clear that renewable fuels of non-biological origin should be included by the member states in the target of 14 % renewable energy in the transport sector by 2030. Recycled carbon fuels are not defined as renewable, but member states *may* still choose to include them in the target. In the year 2021, the commission shall adopt delegated acts both for GHG reduction thresholds and for the methodology that should be used to calculate GHG savings for these fuels. However, it is already in the directive specified that for electrofuels, the share of renewable electricity should be based on the average share in the country of production (two years before), unless electricity is obtained from a direct connection to renewable production. For electrofuels, companies have calculated GHG reductions, based on certified methodologies, of more than 90 % (in Iceland). For fossil waste-based fuels data on 75 % reduction on a well-to-wheel basis can be found (Lanzatech).

On a national level specific policies – existing or planned – related to these fuels are difficult to find. However, the UK includes from April 2018 renewable fuels of non-biological origin in their Renewable Transport Fuel Obligation. Further, they launched already in 2017 a specific funding program for low-carbon waste-based fuels. Information from Germany indicates also a positive view of electrofuels, but there are currently no specific policies in place. In Sweden, the Swedish Energy Agency convey that both electrofuels and waste-based fossil fuels are too far from commercialization to be relevant before 2030, and see, therefore, no reason to specifically develop policies to promote these. In general, we think it is, at this point too early for member states to have analyzed their options for these fuels in relation to the targets and options included in the RED II, not alone to officially declare any intentions.

For each of the three value chains mentioned above, the status of both existing and planned plants are described. In total, four operational plants for the production of electrofuels and nine operational plants for the production of fossil waste-based fuels (including aggregate data for India) have been identified. In addition, 20 planned plants are listed, most of which are for the production of fuels based on waste plastics.

Electrofuels

Identified operational electrofuel plants are mostly of pilot-scale, although one exception exists. Carbon Recycling International (CRI) has produced methanol (trademarked as Vulcanol) at its George Olah methanol plant on Iceland since 2012. The current capacity is about 5 million litres per year. Only one larger-scale planned production plant, the Nordic Blue Crude plant in Norway which is scheduled to be operational by 2020, is identified. In addition, CRI has general expansion plans and three pilot plant/demonstration plants are identified, as well as specific plans for three smaller plants.

As can be seen, there are few existing plants and actual production – as well as concrete expansion plans - are limited. The technology is dependent on the availability of low-priced renewable electricity and decreasing costs for collecting CO_2 to be commercially viable.

Fuels based on gases from waste treatment processes or flue gas of non-renewable origin

There are only two operational plants in this group – the Lanzatech plant in China, producing about 60 million litres of ethanol per year from steel mill flue gases, and a plant in the Netherlands where BioMCN increased the capacity in their conventional methanol production plant by reacting CO_2 recovered from biogas production with excess H_2 available from the process. Specified planned plants are restricted to the expansion of Lanzatech through three additional plants in India, South Africa and Belgium.

Fuels based on waste plastics and/or rubber

Concerning plastic-to-fuel plants, there are currently quite a few commercial plants with a total capacity of about 70 million litres of diesel-type fuels spread between Europe (UK, Ireland and Spain), the US and Asia (China and India). However, no specific plans for new plants have been identified in connection to the companies involved in these operational plants. All planned plastic-to-fuel plants are instead developed by companies without previous commercial-scale experience of the technology they propose to use. Industrial actors with substantial plans for plants to be constructed within the next few years include especially Quantafuels, planning for plants in Denmark, Norway and the Netherlands, and Integrated Green Energy Solutions, which primarily plan to build plants in the UK and the US.

Summarizing the plant capacities for all synthetic fuels (including both electrofuels and fossil waste-based plants, but excluding idled plants), the current global production capacity is about 1150 GWh (150 000 m^3) and the near-term specific expansion plans amounts to about 11 600 GWh (1 200 000 m^3). As a result, the current capacity for synthetic fuel production is about 2.6 % of that of the total capacity of liquid biofuels (according to the former report produced within this project; Production of liquid advanced biofuels – global status), which, in turn, is about 3.5% of total fuel used for transportation.

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

The purpose of this study is to provide an overview of current and future global production of bio-methane and synthetic fuels for use in the transportation sector. The study is made on assignment of the Norwegian environment agency.

For bio-methane, the overview is based partly on publicly available statistics on production and use of bio-methane, partly on assessments of future potential. For synthetic fuels, production levels are very low and aggregate production is not reported in publicly available statistics. The overview is instead based partly on a mapping of existing and planned production plants, partly on a review of policy documents of relevance for the future development of the production of synthetic fuels.

With the purpose above in mind, the scope of the study can be further clarified in the following way for production of bio-methane and synthetic fuels, respectively.

Production of bio-methane

- Production of bio-methane based on anaerobic digestion is a small-scale commercial biofuel conversion technology, meaning that there are a very large number of existing and planned plants worldwide. The bio-methane markets for anaerobic digestion vary substantially between different countries from heating, electricity generation to upgrade for injection into the gas grid or use as transport fuel.
- The developments of bio-methane from gasification are on the other hand currently almost on a stand-still.
- For this group, the description of current production, potential and linkages are therefore made in more general terms and no lists of specific plants are included.
- Current technology trends of relevance for bio-methane as transportation fuel are presented.
- Production of bio-methane from hydrogen and carbon dioxide is included in synthetic fuels.

Production of synthetic fuels

- Synthetic fuel production plants (existing and planned) are too few and too small to produce significant volumes in the near future (to 2030). Additionally, many of the proposed process concepts have yet to be proven on a commercial scale. Consequently, no assessment of current and future production levels have been made and the mapping should be seen as an overview of the most important actors and developments within the field.
- Due to the small number of large scale production plants for synthetic fuels, demonstration and even pilot scale plants have been included in the mapping. Lab-scale pilots are however excluded. If commercial scale plants have been commissioned or are currently being constructed, the related pilot- and demonstration scale projects are generally not included in the overview.

- In the mapping of production plants for synthetic fuels, planned production plants are included only when plant specific details have been announced.

1.2 THE REPORT

In this report, Chapter 2 is focused on the production and use of bio-methane. The chapter provides an overview of current and potential bio-methane production levels. This chapter also includes a discussion about drivers and barriers for the use of bio-methane in the transportation sector, and a review of recent and ongoing technological developments.

Chapter 3 describes global developments related to the production of synthetic fuels. A technological description of the value chains considered in this report is given, as well as a review of related policy aspects. The production plant inventory established in this study is presented and discussed in Chapters 3.3 and 3.4.

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.

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.

Synthetic fuels – Fuels not based on hydrocarbon resources existing in nature, such as fossil fuels or biofuels, but produced via synthesis of hydrogen and carbon from various sources (e.g., electrofuels).

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

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.

[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 PRODUCTION OF BIO-METHANE

2.1 THE VALUE CHAINS FOR PRODUCTION OF BIO-METHANE

Bio-methane can basically be produced via three different value chains:

- anaerobic digestion (Biogas)
- thermal gasification of biomass (Bio-SNG) or
- fuel from renewable hydrogen and carbon dioxide (Power-to-Gas)

The latter value chain is covered in chapter 3 on synthetic fuels and will not be discussed in detail here. An illustration of the three value chains is given in Figure 1 and in Appendix A.

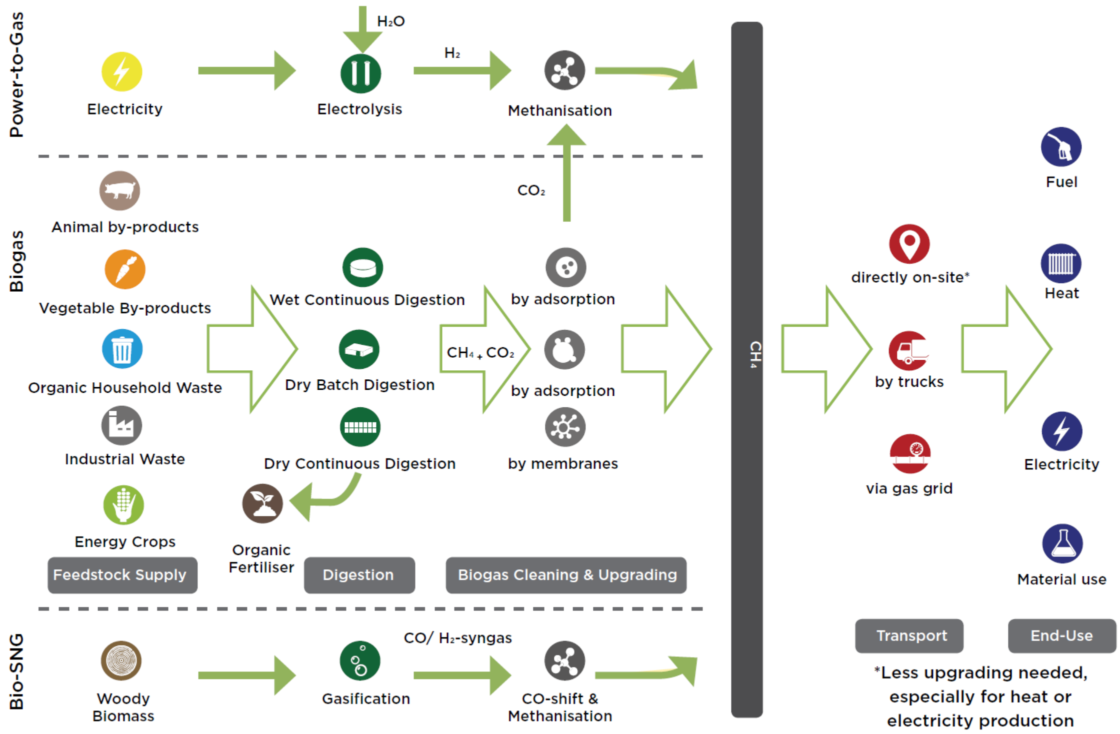

Figure 1: Value chains for bio-methane production (taken from [4]).

Anaerobic digestion of biomass is a rather small scale technology (less than 10 $MW_{biomethane}$) using local feedstock – often waste streams – such as sewage sludge, animal and vegetable by-products, organic household waste or industrial waste. Use of energy crops specifically grown for digestion such as maize or triticale silage is also common, but aspects on competition on land use for food production have to be considered. In Italy, famers increased both the economic viability and stability of agriculture introducing the concept of "Biogas-done-right" [5] based on sequential cropping, thereby avoiding using extra land or competition with feed/food production. This concept could be transferred to large parts of Europe but is hardly applicable to the climate conditions in the Nordic countries [6]. However, a study investigating crop rotation with ley as energy crop for biogas production in southern Sweden concludes that the positive effects of soil carbon content and in combination with the positive greenhouse gas effects of replacing fossil fuels with biogas even can motivate energy crops in the Nordic climate. This applies in particular for cereal intensive areas where soil degradation is a problem and where there is no demand for cattle feed [7].

From a global perspective, biogas from anaerobic digestion is used predominantly for heat and electricity generation. In Europe there are differences between countries, some focusing on combined heat and power production, some focusing on biogas upgrade to bio-methane for injection into the gas grid and/or use as transportation fuel. A limiting factor for the use of upgraded biogas as transportation fuel often is the lack of infrastructure, in the form of fueling stations or an existing nearby gas grid. A number of environmentally sound solutions for biogas upgrade and use as transportation fuel at local scale exist though, such as for example using upgraded biogas for public transport within a municipality.

Biomass gasification for bio-methane production is considerably larger in scale (50 to 500 $MW_{biomethane}$) but not yet commercially available. Two European installations have been operating, namely the Güssing plant in Austria with a themal input of 8 MW_{th} and a demonstration unit for methanation producing 1 $MW_{biomethane}$, as well as the GoBiGas plant in Gothenburg/Sweden with a capacity of 20 $MW_{biomethane}$. Both plants have been demonstration plants at close to commercial scale, but have been struggling with economic viability given the current market situation. The GoBiGas plant is not in operation at the moment and the plant owner Göteborg Energi is considering alternative future use of the plant.[2] It can be concluded that the technology is a stand-still given the current circumstances.

Thermal gasification for bio-methane is rather flexible in feedstock: wood pellets, forest residues, thinnings or short rotation coppice are potential feedstock. Even recycled fossil feedstock such as plastic waste or municipal solid waste (MSW) are potential feedstock for thermal gasification but are not considered here. To be economically viable the plant size needs to be in the 100 $MW_{biomethane}$ range, a recent study based on the experiences of the GoBiGas plant stating that 200 $MW_{biomethane}$ is the most attractive scale for bio-methane production via gasification from an economic perspective [8].

2.2 OVERVIEW OF CURRENT BIO-METHANE PRODUCTION AND POTENTIAL DEVELOPMENT

This section focuses on the production of bio-methane via anaerobic digestion (biogas), since this production strongly dominates. However, in the discussion about future potentials bio-methane is included.

The potential for bio-methane with respect to anaerobic digestion is very much dependent on the local availability of waste streams suitable as feedstock. Biogas production is a way of efficiently using these waste streams, often coupled to a number of other benefits as for example avoided methane emission from manure that is stored in open tanks or improved fertilizer properties of treated manure and sewage sludge. To some extent – and given proper climatic conditions – the biogas potential can be substantially increased with dedicated crops for biogas production avoiding land use competition with food production. The "biogas-done-right"

[2] https://www.goteborgenergi.se/om-oss/vad-vi-gor/forskning-utveckling/gobigas (retrieved 2019-02-01)

concept developed in Italy mentioned earlier is such an example that can increase the biogas potential substantially.

In the EU, total biogas production amounts to in the region of 135 TWh (2013), which mainly was used for delivery of heat (35 TWh in 2015) and electricity (61 TWh in 2015). Germany is the largest biogas producer with about 75 TWh (2013). The electricity generation capacity in Europe in 2015 was 10 GW, compared to 15 GW globally, making Europe the world leader in biogas electricity production [4, 9].

Europe is also the largest producer of upgraded bio-methane for use as vehicle fuel or injection into the gas grid. The fraction of bio-methane from digestion that is actually upgraded to natural gas grid or fuel quality and thus can be used as transportation fuel varies substantially between different countries. This is mainly due to different strategies of using biogas from anaerobic digestion within the energy system. In 2013, Italy, Sweden, Switzerland and France had the highest fractions of total upgraded bio-methane production that was used as vehicle fuel, varying from about 75 % (France) to 100% (Italy) of the total bio-methane production (see Figure 2). Figure 2 refers to upgraded bio-methane and the fraction not used as vehicle fuel is most often injected into the natural gas grid (e.g. Germany and Netherlands). The remainder of biogas (not shown in figure 2, since it is not upgraded) is mainly used for electricity generation in cogeneration units. These figures are comparably old, meaning that exact figures might have changed. However, a general trend of increasing use of bio-methane for public transport or waste recycling vehicles can be observed, as well as large differences between different countries with respect to use of bio-methane specifically as transport fuel. [4]

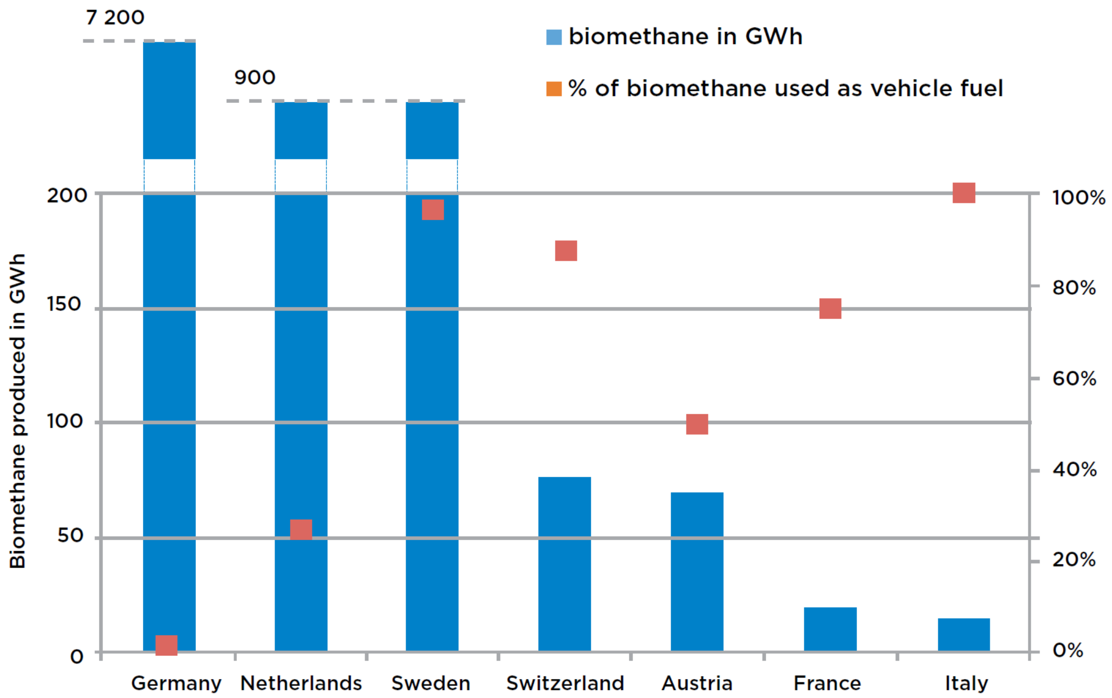

Figure 2: Pure bio-methane production and use as vehicle fuel in countries with most bio-methane production worldwide in 2013 [4].

The differences between European countries are also analyzed and illustrated by a recent master thesis on the European countries' biogas markets [10]. Figure 3 illustrates the maturity and momentum (expected biogas market growth over the next five years) by plotting the expected production increase versus the production in 2017, both specific per capita. In Germany for example a lot of biogas is produced per capita and the market is mature. There is less growth to be expected so the momentum in the market is rather low. Denmark has both a high market maturity and momentum with high production increases expected (per capita). Norway is also considered having a market with high momentum. The indication of high momentum however, again gives no indication on whether the upgrade of biogas as transportation fuel is in focus for the respective country.

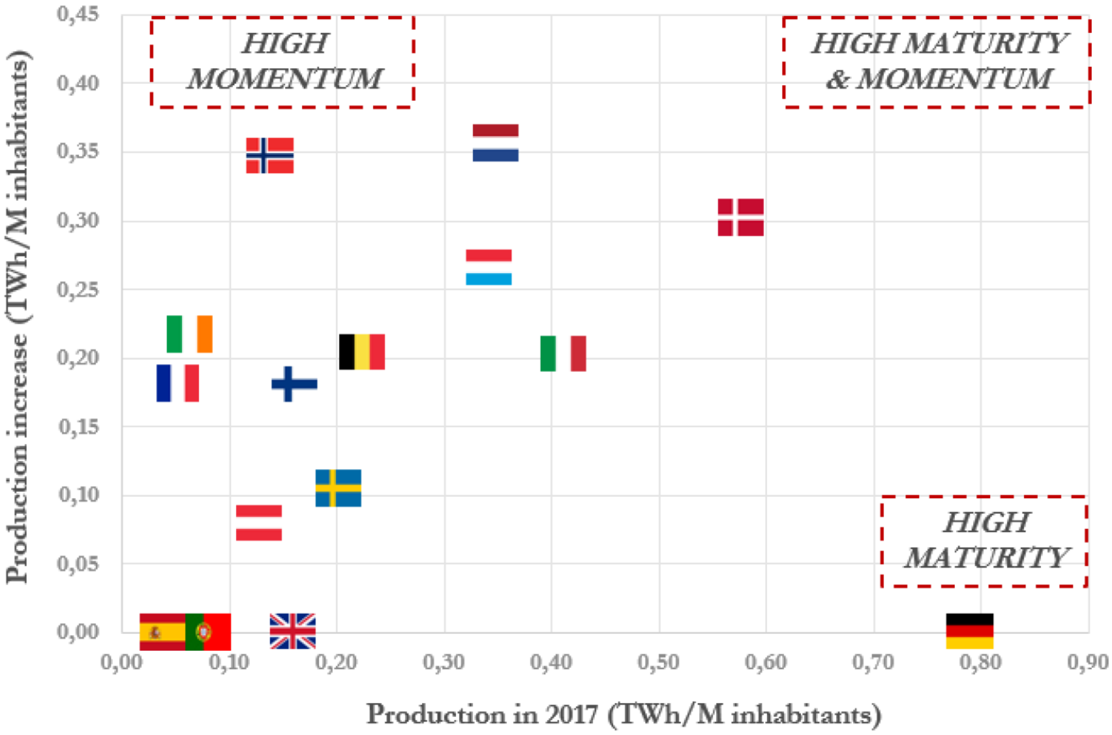

Figure 3: Biogas production per-capita in European countries compared to their momentum (estimated biogas production increase per capita) (taken from [10]).

For Denmark, Sweden, Norway and Finland the biogas production and use as transport fuel in 2017 is presented in Table 1. Sweden has a very strong focus on biogas for transportation with very active regions, in particular where there is a natural gas infrastructure (Västra Götaland, Skåne). The use of biogas as transportation fuel corresponds to 68% of all biogas production[3]. In Norway, the use of biogas for transportation also is more than half of the overall production in energy terms. Denmark, in contrast, has very little biogas use in the transportation sector, the focus there being on balancing the intermittent electricity generation from wind power.

[3] It has to be noted though that about 18% of biogas for transport has been imported in 2017 (mainly from Denmark).

Table 1: Biogas data for Denmark, Sweden, Norway and Finland for 2017 (Data collected from [11-21].

		Denmark	Sweden	Norway	Finland
Number of biogas plants	[-]	166	274	39	97
Number of uppgrading plants	[-]	12[1)]	65	14	17
Total biogas production	[TWh]	3.1	2.1	0.74	1.6
	[million m^3]	338.1	225.6	80.5	172.2
Use of biogas for transport	TWh	0.004	1.4	0.4	0.03
share of production	[%]	0.001%	68%	57%	2%
Compressed/liquefied biogas (CBG/LBG) filling stations	[-]	17	182	35	34

[1)] 2016 years data

The estimated realistic potential for the four countries in total is about 60 TWh as illustrated in Table 2. Avfall Norge [16] estimates that about 10-12 TWh of biogas could be produced from waste streams, corresponding to about 20% of the fuel demand for road based transport in Norway.

Table 2: Estimated biogas production potential for Denmark, Sweden, Norway and Finland [17].

		Denmark	Sweden	Norway	Finland
Biogas potential	[TWh]	10-17	15	10-12	9-24

From a European perspective there are large variations between different estimates of the biogas production potential and the use as transportation fuel. Scarlat et al. [9] collect a number of estimates that are presented and related to the actual production of biogas and its use as transport fuel in EU-28 in 2017 in figure 4.

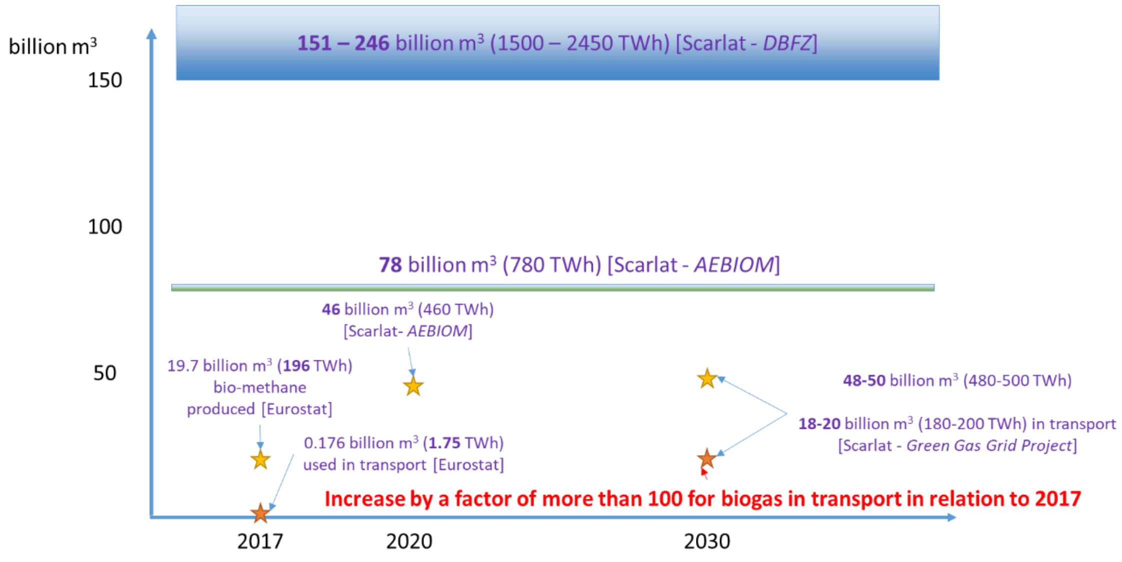

Figure 4: Current biogas production and use in transport (Eurostat [22]) and estimates on biogas production potential in the timeframe up to 2030 [9]. (conversion between m^3 and TWh is based on the lower heating value of methane (35.8 MJ/Nm^3 or 9.94 TWh/billion Nm^3), bold values indicate the original source). The rectangles represent technical potential estimates whereas the stars represent current data (2017) and future estimates of production (yellow) and use in transport (orange), respectively.

The German Biomass Research Centre (DBFZ) estimates the technical bio-methane potential from both digestion and gasification to be in the range of 151-246 billion m^3. Within the Green Gas grid Project, it was estimated that 48-50 billion m^3 bio-methane production could be realized until 2030, with 18-20 billion m^3 being upgraded and available for grid injection and transport applications. The European Biogas Association (AEBIOM[4]) estimated a European bio-methane potential of 78 billion m^3 in total with 46 billion m^3 to be possible to reach by 2020. [9]

A more long term biogas production estimate is given by Ecofys in their "Gas for climate" report [6], with about 98 billion m^3 of natural gas equivalents by 2050. 63 billion m^3 of that estimate originate from anaerobic digestion, the remaining 35 billion m^3 from biomass gasification. A large share of the biomass for anaerobic digestion (generating more than 40 billion m^3 of the total biogas potential of 63 billion m^3 from anaerobic digestion) is assumed to originate from sequential energy crops according to the "Biogas-done-right" concept mentioned earlier. It is accounted for that this concept is hardly feasible in certain climatic regions such as the Nordic countries.

[4] Now "Bioenergy Europé" - https://bioenergyeurope.org/ (retrieved 2019-02-26)

Based on the above mentioned potential estimates and given the large share of energy crops these potential estimates rely on, a more realistic long term potential for biogas production in Europe can be considered to be at around 50 billion m^3 (or 500 TWh). The fraction of biogas that will be used within the transportation sector will depend on a number of factors and is hard to estimate. The fraction of about 40% of the total biogas production potential by 2030 used for transport indicated by the Green Gas Grid Project [9] is a reasonable estimate on a European level. This would imply an increase of biogas use in the transport sector by a factor of more than 100 in relation to 2017.

No specific global developments with respect to biogas as transportation fuel can be identified. According to IRENA [4], countries with the greatest potential to establish a biogas-for-transport market in the near future are China, the US, India, Germany and Brazil. This is based on the existing natural gas vehicle and filling station infrastructure and a large biogas production potential (basically due to large populations generating large amounts of waste suitable as feedstock for digestion).

2.3 SPECIFIC TECHNOLOGY DEVELOPMENTS OF INTEREST

One of the often mentioned drawbacks of bio-methane for efficient use as transportation fuel, namely being dependant on a (local or national) gas grid infrastructure, can be circumvented when producing liquefied bio-methane, often also referred to as liquefied biogas (LBG). This allows for a more efficient distribution of the gas and opens up for a multiple of transport applications such as heavy duty transport or shipping. Liquefaction technology has historically been a large scale technology, but there are a number of plants installed that produce LBG from digestion plants. One example is the LBG plant in Lidköping, Sweden[5], producing 6 million Nm^3 bio-methane per year, corresponding to about 55 GWh/y or 6 $MW_{biomethane}$ (compared to a capacity of e.g. the LNG terminal in Rotterdam, Netherlands (Gate) of 18 billion Nm^3/yr or about 190 TWh/yr).

Examples of other relevant ongoing technology developments are Renovare Fuels[6], a company proposing an add-on plant on existing biogas plants that directly converts the raw biogas (methane and CO_2) via a Fischer-Tropsch synthesis step into a liquid fuel, either Diesel fuel for road transport or jet fuel for aviation. The company claims economic feasibility for e.g. municipal biogas plants, but given the complexity of the upgrading process and up-to-date scientific literature (e.g. [8, 23]) clearly indicating that economic operation of synthetic fuel (from bio-methane to liquid fuel) production only is feasible in the 100 $MW_{biofuel}$ range and above, the economic viability of the concept can be questioned. In a recent investigation on techno-economics of biofuel production [24], the need for large scale is questioned, but the processes considered with lowest capacity still have a capacity of about 50 $MW_{biofuel}$ and higher, which is considerably larger than the biogas output from biogas plants based on anaerobic digestion.

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[5] Gasum Lidköping AB, https://www.gasum.com/sv/om-gas/biogas/vara-anlaggningar/lidkoping/, retrieved 2019-02-26

[6] Renovare Fuels LtD, http://www.renovare-fuels.co.uk/, retrieved 2019-12-15

Another approach for improving the performance of biogas plants is proposed – among others – by Electrochaea[7] – a company developing a biocatalyst converting CO_2 with H_2 at low temperatures to CH_4. This process allows to upgrade raw biogas to bio-methane quality by adding H_2 from renewable electricity using the CO_2 present in the biogas and thereby avoiding a separation step for biogas upgrade. The biocatalyst operates at moderate temperatures at around 60-65°C in contrast to standard catalytic methanation operating at around 300°C, making it a potentially viable technology for small scale operation. The technology has been demonstrated within the BioCat project[8] in Denmark at a municipal biogas plant and a 1 MW_{el} electrolyzer for H_2 production.

Another technology that is becoming more and more common in connection to biogas production is hydrothermal carbonisation (HTC), in particular in connection to plants based on sewage sludge. HTC is making use of the sludge after digestion, producing a bio-coal that can either be used as fuel or soil enhancer balancing soil carbon degradation. The technology is a promising alternative to traditional handling of sewage sludge (combustion for destruction), but as the process does not affect the output of biogas and the fuel produced is solid it is of no direct relevance to the transport sector.

2.4 DRIVERS AND BARRIERS FOR BIO-METHANE AS TRANSPORTATION FUEL

With biogas, produced via anaerobic digestion, being a local resource resulting in a number environmental benefits and promoting local economic activities it is an obvious choice for waste handling. The choice of final use of biogas for electricity and heat generation or gas upgrade as transportation fuel or natural gas replacement is more complex though. It depends a lot on the existing energy system and infrastructure. Electrification of the transport sector might outperform biogas as a transportation fuel in the long run, but using it for local transport systems or heavy transport and shipping is definitely a viable alternative in the medium term. As liquefaction of bio-methane becomes more and more applicable, infrastructure barriers become less relevant.

Biogas production at small scale is currently still dependent on support schemes – such as investment support or production subsidies (e.g. Gödselgasstöd in Sweden). The multiple environmental benefits motivate such support though.

Bio-SNG from biomass gasification requires plant scales in the 100 MW_{fuel} range that are associated with considerable investments. Long-term policies for support of biofuels or mandatory biofuel blending rates are often considered to be necessary to get the production of gasification based fuels at large scale in place. In addition, Bio-SNG from gasification competes with other gasification based biofuel alternatives such as methanol, FT-Diesel or DME that might be more suitable for use as transportation fuel. The energy conversion efficiency from biomass to Bio-SNG is higher than for liquid biofuels favouring its production, but infrastructure issues are often brought up as drawback. The natural gas grid infrastructure and European Directives on renewable fuel infrastructure [25] requiring a certain geographic coverage of gas refuelling stations (both compressed and liquefied gas) may help to reduce

[7] Electrochaea GmbH, http://www.electrochaea.com/, retrieved 2019-02-15
[8] BioCat project, http://biocat-project.com/, retrieved 2019-02-15

these drawbacks. Further, the role of natural gas as a driving force in the transition to a hydrogen economy is often brought up as a synergy for bio-methane development. Almost 50 % of the global hydrogen production is currently based on natural gas steam reforming and bio-methane could be a drop-in for replacing fossil feedstock.

Finally, there might be considerable synergies between the different value chains of bio-methane production, with biogas from digestion being a viable local alternative, bio-SNG from gasification being a large scale technology, and Power-to-Gas being an option to boost both biogas and bio-SNG production while using intermittent electricity production. Altogether, this makes bio-methane a very versatile energy carrier with a number of different potential applications in the energy system.

The production of liquid biofuels (other than liquefied biogas) using bio-methane as feedstock, should in general only be economically justified for large-scale plants, making it necessary to connect them to Bio-SNG plants via gasification. This is however a considerably more complex process chain reducing the overall biomass-to-fuel efficiency. From an environmental viewpoint it could be justified in case there are no other markets where the bio-methane produced could be used for substituting fossil energy. However, it is difficult to envision an energy system in which this would be the case, with bio-methane being such a versatile energy carrier that can be used for heat, electricity and transport. Moreover, the production of liquid biofuels via gasification can be realised more efficiently without passing the bio-methane step (even though bio-methane could play a role as "drop-in" not needing any process adaptions for common applications in e.g. chemical industry using fossil natural gas as feedstock). The bio-methane potential from anaerobic digestion is limited – as has been mentioned earlier – and can be more efficiently used in a local context at small scale.

3 PRODUCTION OF SYNTHETIC FUELS

Two general value chains for synthetic fuels are considered. These are *electrofuels* and *fossil waste-based fuels*. Below, short technological descriptions of the value chains are given in 3.1, and relevant policy aspects are discussed in 3.2. Existing and developing production plants are presented in 3.3 and 3.4.

3.1 THE VALUE CHAINS FOR PRODUCTION OF SYNTHETIC FUELS

Electrofuels (also known as power-to-liquids, power-to-gas or e-fuels) are produced using electricity as the main energy input. The electricity is used to produce hydrogen which can be used as is or be reacted with CO_2 to produce alcohols or hydrocarbons [26]. CO_2 may be supplied by e.g. capture from industrial point sources or direct air capture (see also Appendix A). The most straight-forward *liquid* electrofuel is probably methanol, which can be synthesised directly from CO_2 and hydrogen. Methanol can be blended with gasoline, although current EU legislation on oxygen content limits methanol in gasoline blends to a maximum of 3 % [27]. Methanol can also be synthesised further into gasoline or diesel drop-in fuels via DME/olefin synthesis, oligomerisation and hydrotreatment [27],[28]. The required process steps are available (TRL9) for both gasoline and diesel production, but the integrated process chain is so far commercially available only for methanol-to-gasoline. The product is compatible with conventional gasoline. [29]

Drop-in fuels can also be produced via Fischer-Tropsch (FT) synthesis, using syngas (produced from CO_2 and H_2 using the reverse water-gas-shift reaction) instead of methanol as the intermediate. The produced FT-crude can be upgraded to gasoline, diesel or kerosene fuels using conventional refinery processes (hydrocracking, isomerisation, distillation).[27], [28], [29].

Fossil waste-based fuels
Two main pathways have been identified for this category. These are *fuels based on gases from waste treatment processes or flue gas of non-renewable origin* and *fuels based on waste plastics*. Note that fuels produced from mixed waste (i.e. containing both fossil and biogenic fractions) were included in a previous report and are not repeated here.

Fuels based on gases from waste treatment processes or flue gas of non-renewable origin
The development of processes for fuel production from flue gases is dominated by LanzaTech. Using a proprietary microorganism, the company produces ethanol by fermentation of CO and H_2 containing flue gases in continuous bioreactors. The process is not sensitive to the $CO:H_2$ ratio and if hydrogen is lacking, the microorganism can produce it from carbon monoxide and water (reverse water-gas shift). So far, the main focus has been on utilising steel mill flue gases (which would otherwise have been flared or used for power production). [30-32]

Gases from waste treatment processes have been used for methanol production by BioMCN. They use CO_2 from biogas production as additional input to their conventional methanol process (which has an excess of hydrogen).

Fuels based on waste plastics and/or rubber
The identified plastic-to-fuel plants generally employ pyrolysis (either thermal or catalytic, with thermal being the more common alternative) or similar technologies (such as hydrothermal depolymerisation) to obtain a pyrolysis oil. The obtained pyrolysis oil is typically classified as a synthetic crude (syncrude) that is miscible with crude oil.

Some identified plants upgrade the pyrolysis product on-site by distillation into various fuel blendstocks, while others sell (or intend to sell) it to refineries for processing. On-site processing typically yields naphtha, diesel, fuel oil and wax fractions, with the diesel fraction being the major by weight output. Note that the quality of the fuel products is uncertain for all identified plants. This includes for example compliance with existing fuel standards, and produced diesel may need further treatment to yield road ready fuels. If the crude product is sold to commercial refineries, the quality is not expected to be a problem.

The technology description provided here is based on [33] and on a combined assessment of the technologies used at the identified plants. Data sources for individual plants are available in Appendix B Plant data for production of synthetic fuels.

3.2 POLICY ASPECTS RELATED TO SYNTHETIC FUELS

In the new EU directive on the promotion of energy from renewable sources, commonly referred to as the Renewable Energy Directive II or REDII [34], the terms synthetic fuels or the value chains mentioned above are not used. Instead, two concepts have been introduced that cover these value chains, namely renewable fuels of non-biological origin and recycled carbon fuels, with the following definitions (our underscoring):

> *Renewable liquid and gaseous transport fuels of non-biological origin* – liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, <u>the energy content of which is derived from renewable sources</u> other than biomass.
>
> *Recycled carbon fuels* – liquid and gaseous fuels that are produced from liquid or solid waste streams of <u>non-renewable origin</u> which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas and exhaust gas of <u>non-renewable origin</u> which are produced as an unavoidable and unintentional consequence of the production process in industrial installations.

This means that renewable fuels of non-biological origin include the value chain(s) we have described as electrofuels above, as long as the energy used for their production is derived from renewable sources. The source of CO_2 is, however, not specified or mentioned in the directive (see also below). They may also include other types of fuels, such as so called solar fuels (generating fuels directly from solar energy), however there are no other value chains than electrofuels that are anywhere near commercial scale implementation. Recycled carbon fuels include gasification of fossil (non-recyclable) waste material and production of transport fuels from industrial fossil off-gases (from for instance the steel industry), i.e. what is above called fossil waste-based fuels.

It should be noted that the definitions used in REDII for these two groups of fuels are quite new, and not used in earlier directives or other EU publications. As a result, the actual interpretations of which processes are included under which category, and with which limitations, are not yet tested by practical policy implementations.

From the directive it is clear that fuels of non-biological origin are defined as renewable fuels and *should* be included by the member states in the target of 14% renewable energy in the transport sector by 2030. On the contrary recycled carbon fuels are not defined as renewable, but member states *may* still choose to include them in the target. For renewable fuels of non-biological origin a GHG reduction requirement of at least 70% is set from 2021. However, the methodology for calculating the GHG reduction from this type of fuels is still to be determined. In the year 2021, the commission shall adopt delegated acts both for the GHG reduction threshold for recycled carbon fuels (in January) and for the methodology that should be used to calculate GHG savings for fuels of non-biological origin *and* for recycled carbon fuels (in December). [34]

The policy-related issues that we have tried to find information about concerning these fuels include:

- How will the GHG reduction potential of these fuels be calculated?
- Are there countries that already promote or include these fuels in their renewable fuel policies?
- Are there any indications on how member states in the EU plan to treat these fuels in their policies that will be developed to fulfil the REDII?

In general, this type of information has been difficult to find – or rather, since the actual production of these fuels is internationally still very small, few countries have had reasons to explicitly include them in their policies or to investigate how they would be affected by current policies. Further, as was mentioned above, the specific methodologies for calculating GHG emissions are not yet developed. Anyways, a few notions for each of the questions are made below. In the following, we focus on the value chains included in this report and use thus mostly the terms electrofuels and fossil waste-based fuels.

<u>How will the GHG reduction potential of these fuels be calculated?</u>

The GHG emissions from electrofuels have been calculated. In a four-year project within the Global CO_2 initiative, hosted by the University of Michigan, methodology guidelines for making LCA studies of CCU (carbon capture and utilization, in which electrofuels are included) have been developed. They describe complex analytical processes and for a full understanding we refer to their publications. In the guidelines, CO_2 is viewed as a resource for the production of goods and the same approach is used regardless of the source of CO_2. However, *results* in terms of GHG reduction potential, may differ between sources, depending also on the assumptions made on which products and processes the electrofuels replace and thus on the surrounding system. Thus, GHG reduction from fossil CO_2 utilization is not in any way ruled out. [35]

In a report by the consultancy firm E4Tech from 2018, a framework for assessing sustainability risks, including the risk that production and use of the fuel will lead to increased lifecycle GHG emissions and risks associated to waste feedstocks (e.g. waste regulations), is developed for both electrofuels and waste-based fossil fuels is developed. Here, they also come to the conclusion that the methodology for calculating GHG from electrofuels (renewable fuels from non-biological origin) is quite different to the existing biofuel methodology. [36]

For the methanol produced by CRI on Iceland (Vulcanol, see below), GHG emissions are calculated based on standard ISCC (International Sustainability Carbon Certification) EU methodology and the process is certified by SGS Germany according to ISCC Plus system. The ISCC certification is recognised by the EU commission as a voluntary scheme that, through certification, provide evidence of compliance with the EU sustainability criteria, and is widely used. According to the company website, the reduction is more than 90%. [37]

For biofuels, the methodologies used for calculating GHG reduction coincide in principle with the ones used in the EUCAR/JRC/CONCAWE well-to-wheel studies of life-cycle emissions from various fossil and bio-based fuel value chains [38]. There is currently work going on with a new version (version 5) of this study, in which at least some value chains for electrofuels are expected to be included. However, the publication of this report has been delayed to mid-2019 and there is currently no publicly available information [39].[9]

The issues that may impact the calculations are partly the treatment of the electricity used for production, partly the view of the origin of CO_2-streams used in the production. The directive specifies that the share of renewable electricity should be based on the average share of electricity from renewable sources in the country of production, as measured two years before the year in question. The exception is if electricity is obtained from a direct connection to *new* renewable electricity production, which is not connected to the grid [34].

There are no specifications in the directive relating to the origin of the CO_2-streams (fossil or of biological origin) for electrofuels. The only specification is that the energy content of the fuels should be derived from renewable sources (the energy content of CO_2 is zero). Thus, the general view seem to be that the origin of CO_2 will not impact the definition electrofuels as renewable fuels. Several persons have also indicated that this was an issue in earlier versions of the RED II, but that it was subsequently sorted. However, a final clarification will be made, at the latest, in the delegated act on methodology in December 2021.

In the report from E4Tech, risks and methodologies for various types of fossil waste-based fuels are discussed as well. [36] In addition, there are some examples of GHG reduction calculations from company information. Lanzatech quotes a reduction of GHG at about 75% on a well-to-wheel basis and Quantafuels a 85-90% reduction in the fuel production process.[10] Further, to a large extent the focus is put on recycling into new plastics or chemicals, rather than on fuel production. On the other hand, it is clear that the companies developing these technologyies focus their marketing mainly on the environmental advantages of increased recycling,

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[9] The preliminary report was presented at the conference "Internationaler Motorenkongress 2018" [40] thus a larger group of people has seen preliminary results. However, this conference presentation is not freely available and therefore could not be included in this report. A preview of the results is planned for well-to-tank and tank-to-wheel separately in Brussels in early April 2019 [39].

[10] Lanzatech refer to calculations made by Sustainable Biomaterials (RSB), Tsinghua University in China and Michigan Tech University in the USA as well as the assessment group of E4Tech in London. For Quantafuels there are no information about the source or methodology used.

contributing to cleaning-up of plastic waste (for instance in the oceans) and reduction of oil dependency, even though reduction of GHG is also included. [41-43]

It is quite clear that for recycling shares, the mass balance principle is widely accepted also for this type of value chains (as for the shares of biofuels in blended in fossil fuels). Other principle issues that are under discussion are, of course, to what extent recycling of fossil material reduce the use of fossil resources and the linkage to GHG emissions.

<u>Are there countries that already promote or include these fuels in their renewable fuel policies?</u>

The methanol produced on Iceland (Vulcanol) has been sold to, among others, Perstorp Bioproducts which has used it in smaller shares for their production of RME and to Varo Energy, a European fossil refinery and fuel distributor, which has used it for blending in gasoline. In both these cases it seems that the GHG reduction provided by ISCC certificate of the producer CRI have been acknowledged in the certification of their final products, which also seem reasonable, given that the scheme is recognized by the commission. From what we have found there are, however, no guidelines or parts of the policy frameworks that specifically relates to electrofuels in the countries where these have been used. It should be noted that the volumes are also very small and only affects GHG reduction of final fuels marginally. [37, 44]

In Germany, the German Energy Agency (dena) launched, in September 2018, the "Global Alliance Power Fuels" as a broad initiative gathering industry, research and politics to foster the development of global markets for synthetic fuels based on renewable energy sources [45]. The initiative is a follow up on a study on the integrated energy transition where the roll of synthetic fuels has been analysed. Recommendations on actions based on that study include:

- Build-up of international markets as it is recognized that other regions in the world might have more favorable conditions to produce e-fuels,
- Focus on carbon-free generation of hydrogen,
- Aim for common European credibility of Power Fuels with respect to GHG emission reduction and manufacturers' vehicle fleet emission targets,
- Short term (time-limited) policy instruments for market introduction of power-to-gas and power-to-fuels facilities,
- Further development of the infrastructure for both liquid and gaseous fuels, including the development of a roadmap for use of liquid synthetic fuels in Germany.

This initiative indicates a positive view of electrofuels, but also that there are no specific methodologies or policies yet in place.

In the UK, the Renewable Transport Fuel Obligation (RTFO) as changed in April 2018. In addition to increased biofuels targets and introduction of a specific target for advanced biofuels, the changes included specifically to bring "renewable fuels of non-biological origin" into the scheme. It can be noted that this is thus exactly the same term that has later been introduced in the RED II. [46]

For the recycled carbon fuels, there are fuels produced in Spain, the UK and Ireland (in Europe), which might give an indication of countries that see these technologies as more relevant for the development of sustainable transport. In the UK, a specific funding program of, in total, 22 million pounds, for low-carbon waste-based fuels for heavy vehicles and aviation was launched in August 2017 [47]. Further, the E4Tech report includes a discussion on alternative options and some recommendations for the UK department of transport for how to include non-renewable low-carbon fuels in the policy support schemes aiming at decreasing GHG emissions from transport. One of these being to widen the range of fuels supported under the UK “GHG mechanism”, which govern support for low-carbon fuels that do not count as renewable [36]. Consequently, at this point they are included neither in the RTFO scheme, for increasing shares of renewable fuels, or in the GHG mechanism.

In addition, since these processes are developed to handle waste, they are of course subject to waste management policies on both European and national levels. Since this extensive policy area is outside our area of expertise, we have, however, not been able to include a review of these aspects in this report.

<u>Are there any indications on how member states in the EU plan to treat these fuels in their policies that will be developed to fulfil the REDII?</u>

Renewable fuels of non-biological origin *should* thus be included in the member states calculations of their renewable fuels share. However, there are no requirements in the directive on the type of policies that should be used for promoting renewable fuels or that these should be the same for e.g. biofuels and fuels of non-biologial origin. For recycled carbon fuels, the member states choose themselves if including them or not.

For both these two groups we have found few unambiguous indications from any member states on how they intend to incorporate them in their transport fuel policies (see, however, information about UK policy above). The Swedish Energy Agency convey that both electrofuels and waste-based fossil fuels are too far from commercialization and will be too costly to be of relevance, at least during the 2020:s and that therefore the compliance will be dependent on biofuel [48]. They see, therefore, no reason to, at this point, specifically develop policies that promote these fuels (not including actions directed at research and innovation).

In general, we think it is, at this point, too early for the member states to have analyzed their options for these fuels in relation to the targets and options included in the REDII, not alone to officially declare any intentions.

3.3 EXISTING AND OPERATIONAL PLANTS AND PRODUCTION

Operational electrofuel (power-to-liquid) plants using CO_2 feedstock are summarized in Table 3 below. Since commercial scale electrofuel plants are rare, Table 3 also includes larger pilot plants. The production plants have been identified mainly using the two sources listed below:

- A 2018 report for the UK Department for Transport by consultancy firm E4tech, which reviews several value chains for production of low carbon fossil fuels [36]. This report also includes examples of operational and planned production plants connected to each value chain.
- A 2016 report by The Global CO_2 Initiative (connected to University of Michigan) mapping companies targeting carbon capture and utilization (CO_2U) technologies [49]. This report includes an assessment of the potential of the involved companies, technological feasibility, readiness and market status.

- A 2017 report prepared by Cerulogy for Transport and Environment[11], assessing the future role of electrofuels in Europe [27].

Complementary data have been obtained from sources such as company reports and web sites, and from news articles. While listed as operational, the actual status of the pilot plants listed in Table 3 is uncertain. Most of them are likely operated discontinuously or in campaigns and idled for long stretches of time.

Table 3: List of operational electrofuel (power-to-liquid) plants.

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
George Olah methanol plant	Operational	CO_2	Methanol	22 (5 050)
Sunfire Dresden (Pilot)	Operational	CO_2 (air capture)	FT-crude	0,46[1,2] (44)
Mitsui Osaka Works (Pilot)	Operational	CO_2	Methanol	0,56 (126)
Carbon Engineering DAC (Pilot)	Operational	CO_2 (air capture)	Not specified	0,46[1] (44)

[1]Assuming LHV=38.2 MJ/kg
[2] the product crude has been used to produce Audi "e-diesel" but it is not clear whether refining took place on- or off-site (https://www.audi-mediacenter.com/en/press-releases/fuel-of-the-future-research-facility-in-dresden-produces-first-batch-of-audi-e-diesel-352)

Identified electrofuel plants are mostly of pilot-scale, although one exception exists. Carbon Recycling International has produced methanol (trademarked as Vulcanol) at its *George Olah methanol* plant on Iceland since 2012. Current capacity is about 5 million litres per year. This plant uses CO_2 captured from a nearby geothermal power plant, and produces the required hydrogen using grid electricity. [36, 49, 50]

Sunfire and *Audi* began operating a pilot plant in Dresden, Germany in 2014 [29]. This plant produces FT-crude from hydrogen and CO_2. The required CO_2 is (at least partly) supplied via direct air capture, using the technology of project partner Climeworks. [29, 51] A commercial scale plant based on the same technology is planned for 2020 (see 3.4) [52].

Mitsui Chemicals now have almost ten years of experience from operating an electrofuel pilot producing methanol from CO_2 contained in the flue gases of their *Osaka Works* facilities [49, 53]. In their 2018 ESG (environmental, social and governance) report [54], the company claim to continue pursuing commercialization and investigate various business models. Securing a hydrogen supply is mentioned as a major hurdle.

[11]Transport and Environment: https://www.transportenvironment.org/

Carbon Engineering is operating a pilot for producing diesel-type fuels using direct air capture [55].

Companies and production plants targeting <u>fuels from fossil waste</u> are listed in Table 4. The production plants have been identified mainly using the three sources listed below:

- A 2018 report for the UK Department for Transport by consultancy firm E4tech, which reviews several value chains for production of low carbon fossil fuels [36]. This report also includes examples of operational and planned production plants connected to each value chain.
- A 2015 report by the Ocean Recovery Alliance [33]. This report identifies technology providers in the plastic to fuel sector and lists operational production plants (as of 2015).
- A 2017 report by consultancy firm Ricardo Energy and Environment [56]. This report includes a worldwide overview of operational and planned plastic to fuel plants.
- The International Energy Agency's Advanced Biofuels Demoplants database. While mainly focusing on biofuels, this database also includes production plants using waste gas feedstock (e.g., various industrial off-gases) [30].

Complementary data have been obtained from sources such as company reports and web sites, and from news articles. It must be noted that actual production data has not been obtained for any of the plants in Table 4 and that capacity utilisation may be very low, since it mostly concerns new plants and more or less non-proven technologies.

Compared to the electrofuel plants, identified plants (planned or operational) are larger in size and more numerous. For this reason, Table 4 does not include pilot scale plants. The plants can be divided into two main groups: plants using gases from waste treatment or off-gases of non-renewable origin (*LanzaTech* and *BioMCN* are the only companies in this group) and plants utilising a feedstock consisting of plastic (and/or rubber) waste.

LanzaTech has commercialized a process for ethanol production by fermentation of industrial off-gases in a continuous bio-reactor. After operating several pilot- and demonstration scale plants, the company commissioned its first commercial scale plant in Caofeidian, China last year (2018). This plant has the capacity to produce about 60 million litres of ethanol per year from steel mill flue gases. The company plans to have three similar plants in operation by 2020. Since the company now has commercialized their technology, the company's pilot projects are not listed in Table 4. [30, 57]

Recently, methanol producer *BioMCN* increased capacity at their Farmsum plant by reacting CO_2 recovered from biogas production with excess H_2 available in their conventional methanol process. This means that the energy content of the fuel is derived from non-renewable sources, and that it should be included in this group as long as this is considered a waste stream. The CO_2 is processed with synthesis gas in a conventional methanol converter and reacts with excess H_2 to increase methanol production. Production capacity from recovered CO_2 is just below 19 million litres/year. [36, 58, 59]

In the past decade, three commercial plastic-to-fuel plants were constructed based on the technology developed by UK based company Cynar PLC. Two of these are located in Spain and are owned by Plastic Energy and the third is located in Avonmouth, UK and is owned by SITA

(UK subsidiary of recycling company Suez). The three facilities have an annual production capacity of 5.7 million litres per year each. This volume includes naphtha and diesel fractions, although product splits are not clearly specified. [33, 36, 56]

Cynar has also operated a demonstration plant (2.9 million litres per year capacity) in Portlaoise, Ireland [33].

The company Cynar went into administration in 2016 [36, 60] and the Irish plant is thought to be shut down (idled).The Avonmouth plant has been reported to produce diesel on spec, but there is no indication that the plant is operational, and also this is believed to be idle [60, 61]. The two facilities in Spain are claimed to be operational by Plastic Energy [62], but no publicly available production data has been identified and capacity utilization may be very low. Only the two Spanish plants are included in Table 4, while the idled plants are included in Table 6 (see Section 3.4).

American company *Vadxx* process waste plastics by thermal depolymerisation to obtain a synthetic crude that is upgraded to diesel, naphtha [36, 63, 64]. The company has operated several pilots at various scales and began operating a demonstration plant in Akron, Ohio in 2017 [63, 64]. The company expected to reach full capacity (about 10-15 million litres per year) in 2018 [36]. However, no publicly available production data have been found.

In China, American company Plastic Advanced Recycling Corporation (PARC) operates two plants in Jiangsu province with a combined annual production capacity of roughly 7.7 million litres of synthetic crude [33, 56, 65].

Synthetic crude from waste plastics is also produced by MK Aromatics in India. Production capacity is 2.7 million litres per year and further upgrading is carried out off site in a refinery owned by the company [33, 56].

Technology developer Pyrocrat Systems, also in India, claim that their technology is used in about 20 plants, with a combined production capacity of almost 30 million litres per year of pyrolysis oil [33, 56, 66].

Note that [33] and [56] include several companies or sites in addition to those included in Table 4. These have been excluded following a review, for example because their technology has not yet advanced beyond the small pilot stage, because companies have been dissolved, or because they are no longer aiming to produce liquid fuels but have changed focus to for example plastic recycling or chemicals production.

Table 4: List of operational plants for production of liquid fuels based on fossil waste feedstock. Note that the quality of produced fuels (other than alcohols) is, in general, uncertain and further processing may be required to comply with fuel standards.

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
Fuels based on gases from waste treatment processes or flue gas of non-renewable origin				
LanzaTech Shougang (China)	Operational	Steel flue gas (CO, CO_2, H_2)	Ethanol	359 (60 840)
BioMCN Farmsum (Netherlands)	Operational	CO_2	Methanol	84 (18 900)
Fuels based on waste plastics and/or rubber				
Vadxx Akron (USA)	Operational	Plastic waste (HDPE, LDPE, PP)	Diesel, naphtha	138[1] (13 685)
Plastic Energy Seville (Spain)	Operational	Plastic waste (HDPE, LDPE, PP, PS)	Diesel blendstock, naphtha	58[2] (5 700)[3]
Plastic Energy Almeria (Spain)	Operational	Plastic waste (HDPE, LDPE, PP, PS)	Diesel blendstock, naphtha	58[2] (5 700)[3]
PARC Jiangsuu (2 plants) (China)	Operational	Plastic waste (all grades)	Synthetic crude	35+46 (3 290 + 4 400)[3,4]
MK Aromatics (India)	Operational	Plastic waste (HDPE, LDPE, PP, PS)	Synthetic crude	29 (2 690)[3,4]
Pyrocrat Systems – Aggregate (India)	Operational	Plastic waste (HDPE, LDPE, PP, PS), rubber	Pyrolysis oil[5]	316 (29 800)[3,4]

[1] Assuming liquid output is diesel only. Vadxx do not specify the naphtha/diesel product split. Total liquid fuel production capacity is 115 000 barrels/year. Diesel product is claimed to be suitable for blending with fossil diesel.
[2] Assuming produced fuel is diesel only. Product split is not clearly specified.
[3] Calculated from feed rate and fuel product yield available in [33].
[4] Calculations assume LHV 38.2 MJ/l, rho=1 kg/l
[5] Suitable replacement for industrial diesel according to the company [66].

3.4 DEVELOPING AND IDLE PRODUCTION PLANTS

This section includes developing or idled plants for the two synthetic fuel value chains used in this report. In this context, developing plants include plants that are planned, under construction or in commissioning.

Developing electrofuel (power-to-liquid) plants using CO_2 feedstock are summarized in Table 5 below. Concerning planned plants**,** this table includes only plans for specific plants and not information based on statements concerning general expansion. Some additional companies have published plans for commercial scale plants, but have not announced any specific information (location, start-up year, capacity etc.)

Nordic Blue Crude have plans for a commercial scale electrofuel plant located in Porsgrunn, Norway. The plant is expected to produce synthetic crude diesel from CO_2 and production is scheduled to begin in 2020 [52]. The fuel synthesis technology is provided by Sunfire, who have operated a pilot plant in Dresden, Germany since 2014 (see Table 3). Hydrogen will be produced using renewable electricity and carbon dioxide will be supplied (at least partly) by direct air capture technology developed by Climeworks [52]. Climeworks' technology has been demonstrated at scales up to 2.5 tonnes CO_2/day, in a project where the captured CO_2 is used to boost vegetable growth in a greenhouse [67]. Climeworks also provided a direct air capture unit for the existing Sunfire pilot plant [51].

Audi (who have also been involved in the Sunfire Dresden project) are planning an additional electrofuel pilot connected to a hydropower plant in Laufenburg, Switzerland. Ineratec will provide the reactor technology for the project, which will utilise FT-synthesis to produce about 200 m^3/year of diesel. Production is expected to begin late 2019. The CO_2-source is not specified. [68], [69]

Carbon Recycling International (CRI) plans a roll out of commercial plants in the 60 million litres per year capacity range (about 12 times the size of their George Olah-plant, see Table 3) in addition to their existing plant in Iceland [70]. However, no plant specific details have been found and the company's commercial scale plans are therefore not listed in Table 5. CRI are also involved in the development of two research pilots (for methanol production) with EU Horizon 2020 funding [71, 72]. The FReSMe project [71] will demonstrate the use of CO_2 captured from the blast furnace of a steel mill. A pilot will be built in 2019/2020 in connection to Swerea MEFOS's facilities in Luleå, Sweden. The MefCO2 will use CO_2 captured from a coal fired power plant and surplus intermittent electricity. Pilot plant operations are expected to begin early this year. [72, 73]

Carbon Engineering, currently operating a pilot plant for electrofuel combined with direct air capture, plan to go commercial by 2021 but have yet to announce specific plans for production plants. [55]

Table 5: List of developing electrofuel (power-to-liquid) plants (under construction or planned).

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
Nordic Blue Crude (Norway)	Planned	CO_2 (air capture)	Syncrude	85 (8000)[1]
Ineratec Laufenburg (Switzerland) (Pilot)	Planned	CO_2 (unspecified origin)	Diesel	2,02 (200)
FRESME (Switzerland) (pilot)	Under construction	CO_2 (captured from blast furnace gas)	Methanol	Unknown
MefCO2 (Germany) (pilot)	Under construction	CO_2 (captured from coal power plant)	Methanol	1 ton/day

[1] Assuming LHV=38.2 MJ/l and density 1kg/l

Developing and idled plants for production of synthetic fuel from fossil waste are summarized in Table 6. Most plants plan to utilise waste plastic feedstock, while the plants developed by LanzaTech process industrial off-gases, and BioMCN use CO_2 from biogas production.

LanzaTech commissioned their first commercial scale plant for production of ethanol from steel flue gases in 2018 (see Table 4) and three additional plants are planned or under construction: one in India, one in South Africa and one in Belgium. All three are similar in size to the already operational plant, and use similar feedstocks (steel flue gas, refinery off-gas and ferro-alloy off-gas). [30, 57]

Concerning plastic-to-fuel plants, no specific plans for new plants have been identified in connection to the companies listed in Table 4. The largest operational plastic-to-fuel plant is the Vadxx Akron plant. Vadxx seem to aim at licensing their technology, and hence have no plans for building and operating more plants of their own [64]. No plans have been identified for Plastic Energy, operating two plants in Spain. However, it can be noted that the technology provider for those plants (Cynar PLC) went into administration in 2016 [36]. Information regarding PARC, Pyrocrat Systems and MK Aromatics, all of which operate plants in China and India, is very scarce and no specific future plans have been identified.

Consequently, all plastic-to-fuel plants listed in Table 6 are developed by companies without previous *commercial-scale* experience with the technology they propose to use. A few plants are planned for this year (2019). Renewlogy (previously PK Clean) are commissioning a plant built in collaboration with Canadian recycling company Sustanetech [74, 75]. The company has operated a pilot in Utah since 2014 and the new plant has the capacity to produce about 3.5 million litres per year of diesel fuel [33, 76]. A plant of similar size is planned in Phoenix, Arizona, probably for commissioning around 2020/2021 [77].

Norwegian Quantafuel's convert plastic waste to fuel using a three stage process. After pyrolysis, the resulting oil is fed to a catalytic fuel reactor which increases the alkane content before distillation into diesel, gasoline, fuel oil and light fractions. Diesel is the dominating by-weight output and the company claims that the fuel products can be used without further processing in a refinery [78]. In 2019, following ten years of technology development, production is expected to start at the company's first commercial plant located in Skive, Denmark [78, 79, 80]. This plant will have the capacity to produce around 18 million litres of fuel from plastics each year [78]. The company has announced specific plans for at least two additional plants: one similarly sized plant in Norway and a significantly larger plant (80 million litres) located in the Netherlands [78, 81]. The latter project is a 50/50 joint venture with energy and commodities company Vitol, who have also signed an off-take agreement for the remaining Quantafuel plants [79].

Integrated Green Energy Solutions (IGE, previously FOY Group) have plans for several large-scale plants; one is currently under construction in Amsterdam, Netherlands (planned start-up 2019) and four more are planned in the UK and in the US [36, 82, 83]. The company has a demonstration plant in Berkeley Vale, with an annual production capacity of about 17.5 million litres of diesel, gasoline and kerosene [84, 85]. Production began in 2015 but processing of plastics seems to have been cancelled due to regulatory issues, and the facility is now used for refining mixed fossil fuels [60, 84-86]. Since production from plastic feedstock has been cancelled, this plant is listed as idle in Table 6. No other pilot- or demonstration plants tied to the company have been identified. This lack of experience, combined with the comparatively large scale of the planned plants (especially the plant in Camden, Indiana) makes realization seem less likely. The realization of the planned projects in the UK and the USA is probably highly dependent of the success of the Amsterdam project.

RES Polyflow have plans for a plant in Ashley, Indiana. The plant will produce 68 ML/y (18 million gallons) of diesel and naphtha blendstocks and is expected to start production in 2019. The project is funded by waste-to-energy company Brightmark Energy and RES Polyflow has entered a fuel off-take agreement with British Petroleum (BP). [87, 88]

UK Company ReNew ELP plan a 15.9 ML/y plant in Teesside, UK. The company plan to use technology developed by Licella and has entered a partnership with Finnish refining giant Neste, who are however not involved in the current project. [89-91]

Swedish company Cassandra Oil and their Spanish partner Valoriza have announced plans for a 48 ML/y syncrude plant[12] [92]. The product is claimed to be compatible with crude oil for co-processing [93].

Finally, two idled plants connected to the company Cynar PLC (which went into administration in 2016) are included in Table 6. These include one demonstration plant in Ireland and UK plant owned by Suez SITA. For more information on the Cynar PLC plants, see Section 3.3.

[12] The two companies already have operations on-site, but do not clearly specify to what extent. Operations began in 2014 with a testing phase. After testing, a processing capacity of 24 000 t/year of plastics was expected by 2015: https://futurenviro.es/en/valoriza-pone-en-marcha-la-primera-fase-de-la-planta-de-valorizacion-de-residuos-plasticos-en-jerez-de-la-frontera-cadiz-2/ Very little information on production levels has been communicated by the company in press releases, but there is no indication that large scale production has been reached. When the 48 ML/y project was announced, present activities on-site were described as technology tests only http://www.cassandraoil.com/sv/Press/Pressmeddelanden/Pressmeddelande/?releaseid=2361867

Table 6: List of developing and idled plants for the production of liquid fuels based on waste fossil feedstock (idle, under construction and planned plants). Note that the quality of produced fuels is, in general, uncertain and further processing may be required to comply with fuel standards.

Plant	Status	Feedstock	Product	Capacity *GWh/y (m^3/y)*
Fuels based on gases from waste treatment processes or flue gas of non-renewable origin				
LanzaTech (India)	Under construction	Refinery off-gas	Ethanol	254 (43 090)
Ghent Steelanol (LanzaTech/Arcelor Mittal) (Belgium)	Under construction	Steel flue gas	Ethanol	464 (78 580)
LanzaTech (South Africa)	Planned	Ferro-alloy off-gas	Ethanol	389 (65 910)
Fuels based on waste plastics and/or rubber				
IGE Demo (Australia)	Idled	Plastic waste	Diesel, gasoline, kerosene	177[1] (17 500)
Cynar Demo (Ireland)	Idled	Plastic waste (HDPE, LDPE, PP, PS)	Diesel blendstock, naphtha	29[1] (2 850)[2]
Suez SITA (UK)	Idled	Plastic waste (HDPE, LDPE, PP, PS)	Diesel blendstock, naphtha	58[1] (5 700) [2]
Renewlogy[3] Nova Scotia (Canada)	Commissioning	Plastic waste (all grades)	Diesel	35,4 (3 500)
Renewlogy[3] Phoenix (USA)	Planned	Plastic waste (all grades)	Diesel	35,4 (3 500)[4]
Quantafuel Skive (Denmark)	Under construction	Plastic waste	Fuel HC (mainly diesel)	182 (18 000)

Quantafuel Fredrikstad (Norway)	Planned	Plastic waste	Fuel HC (mainly diesel)	182 (18 000)
Quantafuel ARA (Netherlands)	Planned	Plastic waste	Fuel HC (mainly diesel)	809 (80 000)
RES Polyflow Indiana (USA)	Planned	Plastic waste (not specified)	Diesel and naphtha blendstocks	687[1] (68 000)
IGE Amsterdam (Netherlands)	Under construction	Plastic waste	Marine diesel oil (low sulphur)	371[5] (35 000)
IGE UK (3 plants) (UK)	Planned	Plastic waste	Not specified[6]	3*707 (3*70 000)
IGE Indiana (USA)	Planned	Plastic waste	Not specified[6]	5 305 (525 000)
ReNew Teesside (UK)	Planned	Plastic waste	Not specified[7]	169 (15 900)[8]
Valoriza Jerez (Spain)	Planned	Rubber and plastic waste	Synthetic crude[9]	509 (48 000)[8]

[1] Assuming produced fuel is diesel only. Product split is not clearly specified.
[2] Calculated from feed rate and fuel product yield available in [33].
[3] Previously PK Clean.
[4] Production capacity is not specified by Renewlogy. But plastic feed rate equals that of the Nova Scotia plant.
[5] Assuming LHV 38.2 MJ/l
[6] The UK plants are claimed to produce "road-ready fuels" (https://www.foygroup.com.au/wp-content/uploads/2017-03-March-17-Quarterly.pdf). The capacity calculations (GWh) assume diesel for road use. The US plant is assumed to produce the same fuel as the UK plants.
[7] The technology is claimed to give a synthetic crude that is miscible with conventional crude oil (https://renewelp.co.uk/process/). It is unclear whether upgrading will take place on-site. The intended end-use of the product of the planned plant is not specified.
[8] Calculations assume LHV 38.2 MJ/l and use the conversion rate (product/feed) claimed by the company.
[9] Quality sufficient for use as refinery feedstock (http://cassandraoil.com/sv/Press/Pressmeddelanden/Pressmeddelande/?releaseid=2070417)

3.5 SUMMARY AND OUTLOOK

Synthetic fuel production plants (existing and planned) are too few and too small to produce significant volumes in the near future (to 2030). Additionally, many of the proposed process concepts have yet to be proven on a commercial scale. Consequently, no deeper assessment of current and future production levels have been made and the mapping should primarily be seen as an overview of the most important actors and developments within the field.

However, summarizing the plant capacities in Tables 3 and 4, and Tables 5 and 6, respectively, shows that the current global production capacity of synthetic fuels (including both electrofuels and fossil waste-based plants, but excluding idled plants) is about 1150 GWh (150 000 m^3) and that the near-term specific expansion plans amounts to about 11 600 GWh (1 200 000 m^3). This can be compared to the total capacity of liquid biofuels from the report Production of liquid advanced biofuels – global status [94][13]. There, the overall capacity of advanced liquid biofuels is estimated to be about 44 000 GWh in 2018 (30 000 GWh if HVO based on PFAD is excluded). Total capacity in about 2025, also based on specific company plans for new plants, is estimated to be about 149 TWh (106 TWh if HVO based on PFAD is excluded). Thus, current capacity for synthetic fuel production is about 2.6 % of that of biofuels (which, in turn, currently is about 3.5% of total fuel used for transportation).

As a comparison, the implementation plan for the area of bioenergy and renewable fuels for transport (Action 8) of the SET-plan quantifies expected volumes and investments in development, demonstration and scale-up needed to reach European targets from now up till 2030. [95] This report divides the challenges between biofuels and “other renewable liquid and gaseous fuels”, which can mainly be interpreted as electrofuels.[14] Waste-based fossil fuels are not included. Here, the targets mentioned for 2030 are 200 TWh for biofuels and 25 TWh for other renewable fuels (25 TWh and 1 TWh, respectively, around 2020/22). Consequently, about 86 % of total investments needed is expected to be used for the expansion of biofuel production.

[13] This is the report that was compiled and delivered early 2019 by CIT Industriell Energi AB, on assignment of the Norwegian environment agency, as an earlier step of the same project.
[14] In addition, developments needed for renewable hydrogen production is described separately, but those investments are in this context negligible.

FINAL NOTES AND DISCUSSION

This report complements an earlier report made on assignment of the Norwegian environment agency from CIT Industriell Energi, delivered in December 2018. The former report gave an overview of value chains for the production of liquid advanced biofuels, and related current and planned production sites. Together these two reports give a quite complete picture of potential renewable fuel production in the shorter (5-10 years) term. In addition, they describe the most relevant value chains for this time perspective and some of their more vital linkages.

Since the focus have been on existing and planned production plants, these reports do not, however, provide a deeper analysis of the potential role of the various value chains in the development of a sustainable transport system in Norway over time. Neither do they include a thorough discussion on the relation in such a system between gaseous fuels, liquid fuels and electricity. Such a complete analysis of the Norwegian transportation system corresponds to a large and long-term research project. However, building on a multitude of systems research already performed and published, a synthesis of current knowledge, adapted for the Norwegian situation and "interpreting" current research status to relevant target groups would provide an up-to-date roadmap that is expected to be valuable as a basis for a wide range of planning processes.

The current report, include two very different groups of transport fuel value chains – partly bio-methane which is fairly well-established, but which has certain limitations related to resource potential and infrastructure, partly synthetic fuels, which are currently much lower on the technological development ladder and where actual production is very limited. It should be pointed out that there is no specific logic behind putting these two groups into the same report, other than that they were not included in the former report.

For bio-methane the clearly dominating value chain to date is anaerobic digestion of waste streams at rather small scale, whereas the large scale value chain via biomass gasification so far only has reached demonstration scale. The development of large scale biomass gasification currently is at stand-still. With respect to transportation fuel, there exist in addition a number of alternative value chains via biomass gasification directly leading to liquid fuels that are more suitable than Bio-SNG production. But there still is a rather large potential for development for anaerobic digestion making use of waste streams, in particular when crop-rotation concepts with energy crops are considered viable. Bio-methane from digestion has a large potential as a local resource for specific transportation applications (e.g. public transport) with a number of environmental benefits. There exist a number of technology developments such as liquefaction of gas or increased bio-methane yield through bio-methanation that can boost the viability of bio-methane from digestion and reduce the often named drawback of biogas being dependant on gas grid infrastructure.

For the group of synthetic fuels, one could argue that this type of overview is almost premature. There are currently very few plants for the production of both electrofuels and fossil waste-based fuels, and those that exist on a "larger" scale have developed under quite different context and policy conditions than are currently under way. The public and political awareness and discussion about these value chains have changed considerably over the last couple of years, which is now manifested by their specific inclusion in the REDII. At this point there remains, however, a substantial lack of clarity related to both principal interpretation of the REDII and on its practical implementation. Within the next year or two many aspects of the development of these value chains are expected to become considerably clearer.

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APPENDIX A VALUE CHAINS

Biomethane via anaerobic digestion

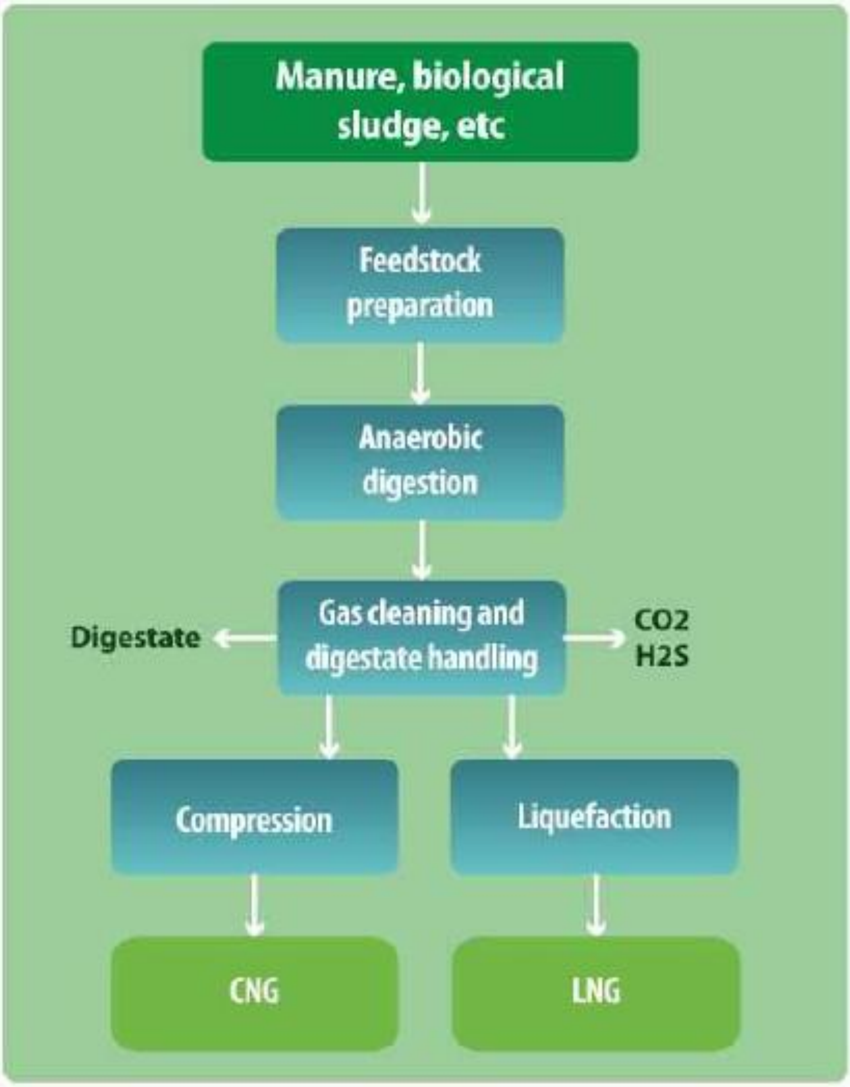

Figure A1: Flow chart of value chain for anaerobic digestions from ETIP Bioenergy [96].

Lignocellulosic feedstocks – Gasification – Biomethane (for transportation)

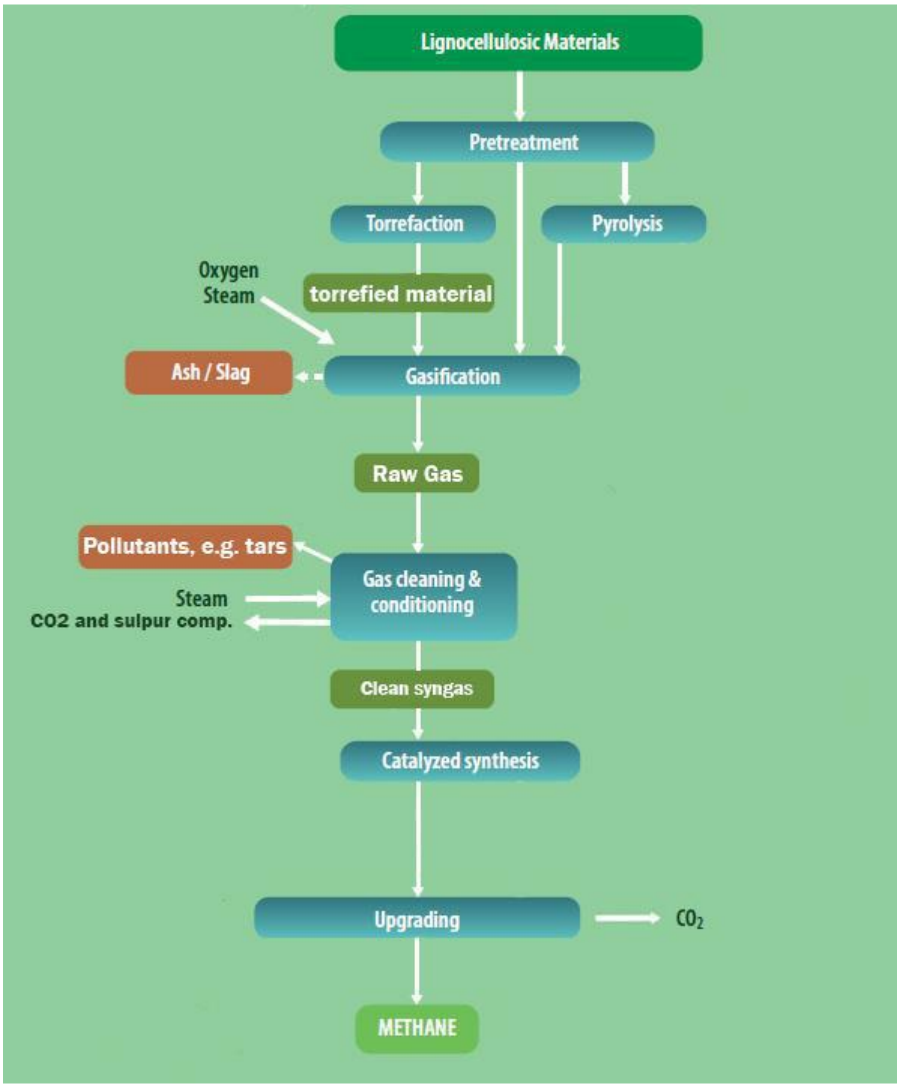

Figure A2: Flow chart of VC2 from ETIP Bioenergy [96].

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

Electrofuels for production of liquid or gaseous transportation fuels

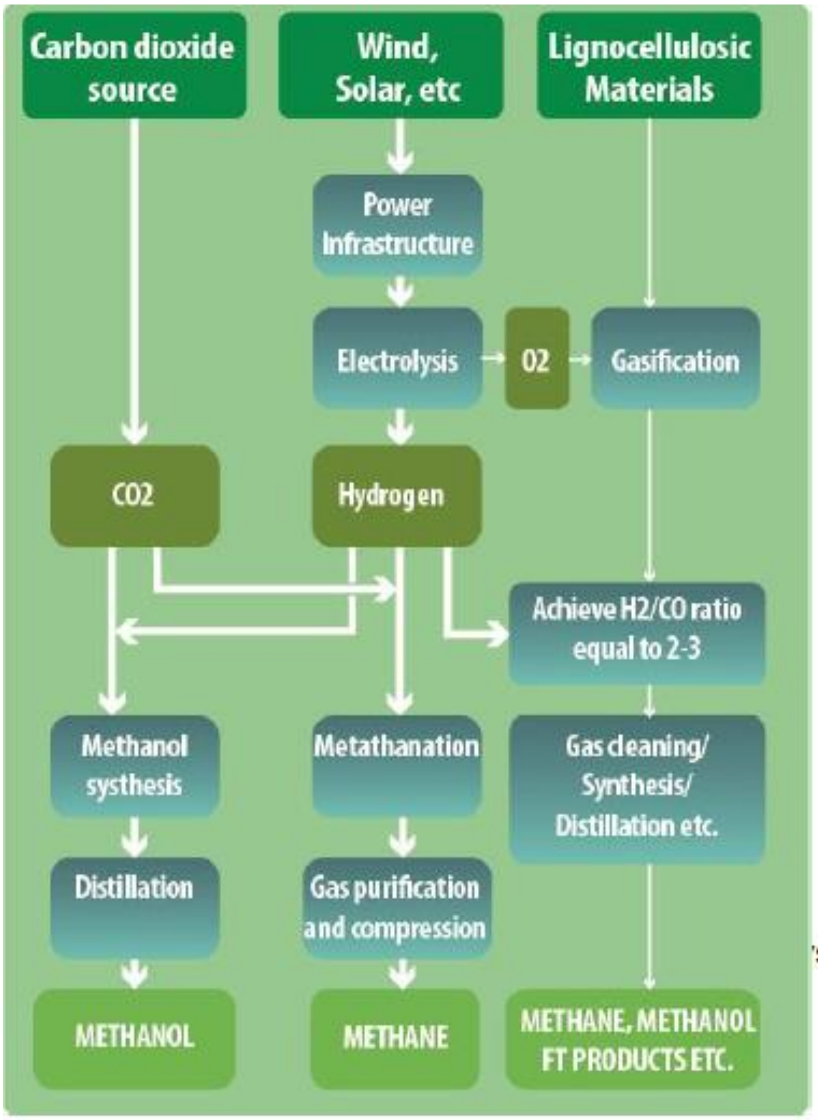

Figure A3: Flow chart of synthetic fuel value chain from ETIP Bioenergy [96].

APPENDIX B PLANT DATA FOR PRODUCTION OF SYNTHETIC FUELS

Table B1: List of operational electrofuel (power-to-liquid) 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
Carbon Recycling International (Iceland)	George Olah methanol plant	Grindavik, Iceland	2012	Operational	CO_2	Methanol	22 (5 050)			36, 49, 50
Sunfire (Germany)	Sunfire Dresden	Dresden, Germany	2014	Operational	CO_2 (air capture)	FT-crude	0,46[1] (44)			29, 51
Carbon Engineering	CE DAC pilot	Squamish, BC	2017	Operational	CO_2 (air capture)	Not specified	0,46[1] (44)			55
Mitsui (Japan)	Osaka Works (Pilot)	Osaka, Japan	2009	Operational	CO_2	Methanol	0,56 (126)			49, 53, 54

[1] Assuming LHV=38.2 MJ/l and density 1kg/l

Table B2: List of developing electrofuel (power-to-liquid) plants (under construction or planned).

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
Sunfire/Nordic Blue Crude (Norway)	Nordic Blue Crude	Porsgrunn, Norway	2020	Planned	CO_2	Syncrude	85[1] (8000)			52
Audi/Ineratec (Switzerland)	Ineratec Laufenburg (Pilot)	Laufenburg, Switzerland	2019	Planned	CO_2 (unspecified origin)	Diesel	2,02 (200)			68, 69
Carbon Recycling International (Sweden)	FRESME (pilot)	Luleå, Sweden	2019/2020	Under construction	CO_2 (captured from blast furnace gas)	Methanol	Unknown			71
Carbon Recycling International (Germany)	MefCO2 (pilot)	Niederaussem, Germany	2019	Under construction	CO_2 (captured from coal power plant)	Methanol	1 ton/day			72, 73

[1] Assuming LHV=38.2 MJ/l and density 1kg/l

Table B3: List of operational plants for production of liquid fuels based on fossil waste feedstock. Note that the quality of produced fuels (other than alcohols) is, in general, uncertain and further processing may be required to comply with fuel standards.

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m^3)	Produced 2017	Investment/economy	References
Fuels based on gases from waste treatment processes or flue gas of non-renewable origin										
LanzaTech (China)	LanzaTech Shougang	Caofeidian, China	2018	Operational	Steel flue gas	Ethanol	359 (60 840)	n/a	21 EUR/MWh	30, 57
BioMCN (Netherlands)	BioMCN Farmsum	Farmsum, Netherlands	2017/2018	Operational	CO_2	Methanol	84 (18 900)			36, 58, 59
Fuels based on waste plastics and/or rubber										
Vadxx (USA)	Vadxx Akron	Akron (Ohio), USA	2017	Operational	Plastic waste (HDPE, LDPE, PP)	Diesel, naphtha	138[1] (13 685)	<34,5 (3420)[2]	25 MUSD	36, 63, 64
Plastic Energy/Cynar (Spain)	Plastic Energy Seville	Seville, Spain	2014	Operational	Plastic waste (HDPE, LDPE, PP, PS)	Diesel, naphtha	58[3] (5 700)[4]			33, 36, 56, 62

Plastic Energy/Cynar (Spain)	Plastic Energy Almeria	Almeria, Spain	2017	Operational	Plastic waste (HDPE, LDPE, PP, PS)	Diesel, naphtha	58[3] (5 700)[4]			33, 36, 56, 62
PARC (China)	PARC Jiangsuu (2 plants)	Jiangsu Province, China	2006/2009	Operational	Plastic waste (all grades)	Synthetic crude	35+46 (3 290 + 4 400)[4,5]			33, 56, 65
MK Aromatics (India)	MK Aromatics	Tamil Nadu, India	2009	Operational	Plastic waste (HDPE, LDPE, PP, PS)	Synthetic crude	29 (2 690)[4,5]	Ca 29[6]		33, 56
Pyrocrat Systems – Aggregate (India)	-	-	-	-	Plastic waste (HDPE, LDPE, PP, PS), rubber	Pyrolysis oil[7]	316 (29 800)[4,5]			33, 56, 66

[1] Assuming liquid output is diesel only. Vadxx do not specify the naphtha/diesel product split. Total liquid fuel production capacity is 115 000 barrels/year. Product is suitable for blending with fossil diesel.
[2] Operations started at 25 % capacity in 2017 according to [36].
[3] Assuming produced fuel is diesel only. Product split is not clearly specified.
[4] Calculated from feed rate and fuel product yield available in [33].
[5] Calculations assume LHV 38.2 MJ/l, rho=1 kg/l
[6] At capacity according to [33]
[7] Suitable replacement for industrial diesel according to the company [66].

Table B4: List of developing and idled plants for the production of liquid fuels based on waste fossil feedstock (idle, under construction and planned plants). Note that the quality of produced fuels is, in general, uncertain and further processing may be required to comply with fuel standards.

Company (and country)	Plant	Location (place and country)	Start-up	Status	Feedstock, current; (potential)	Product (main biofuel)	Product capacity, GWh (m^3)	Produced 2017	Investment/ economy	References
Fuels based on gases from waste treatment processes or flue gas of non-renewable origin										
LanzaTech, Indian Oil (India)	LanzaTech India	Hayrana, India	2020	Under construction	Refinery off-gas	Ethanol	254 (43 090)	n/a	21 EUR/MWh	30, 57
LanzaTech, ArcelorMittal (Belgium)	Ghent Steelanol (LanzaTech/Arcelor Mittal)	Ghent, Belgium	2020	Under construction	Steel flue gas	Ethanol	464 (78 580)	n/a	21 EUR/MWh	30, 57
LanzaTech, Swayana (South Africa)	LanzaTech South Africa	South Africa	2020	Planned	Ferro-alloy off-gas	Ethanol	389 (65 910)	n/a	21 EUR/MWh	30, 57
Fuels based on waste plastics and/or rubber										
IGE (Australia)	IGE Demo	Berkeley Vale (New South Wales), Australia	2015	Idled	Plastic waste	Diesel, gasoline, kerosene	177 (17 500)			60, 84-86

Cynar PLC (Ireland)	Cynar Demo	Portlaoise, Ireland	2010	Idled	Plastic waste (HDPE, LDPE, PP, PS)	Diesel, naphtha	29[1] (2 850)[2]			33, 60
Suez/Cynar (United Kingdom)	Suez SITA	Avonmouth, UK	2015	Idled	Plastic waste (HDPE, LDPE, PP, PS)	Diesel, naphtha	58[3] (5 700)[4]			33, 36, 60, 61
Sustanetech/Renewlogy[3] (Canada)	Renewlogy Nova Scotia	Nova Scotia, Canada	2019	Commissioning	Plastic waste (all grades)	Diesel	35,4 (3 500)	n/a		33, 74-76
Renewlogy[3] (USA)	RenewlogyPhoenix	Phoenix (Arizona), USA	Probably 2020-2021	Planned	Plastic waste (all grades)	Diesel	35,4 (3 500)[4]	n/a		33, 77
Quantafuel (Denmark)	Quantafuel Skive	Skive, Denmark	2019	Under construction	Plastic waste	Fuel HC (mainly diesel)	182 (18 000)	n/a		78-80

Quantafuel (Norway)	Quantafuel Fredrikstad	Fredrikstad, Norway	?	Planned	Plastic waste	Fuel HC (mainly diesel)	182 (18 000)	n/a		78-80
Quantafuel (Netherlands)	Quantafuel ARA	Antwerpen, Netherlands	?	Planned	Plastic waste	Fuel HC (mainly diesel)	809 (80 000)	n/a	90-100 MUSD	78, 81
RES Polyflow (USA)	RES Polyflow Indiana	Ashley (Indiana), USA	2019	Planned	Plastic waste (not specified)	Diesel, naphtha	687[1] (68 000)	n/a	47 MUSD	87, 88
IGE (Netherlands)	IGE Amsterdam	Amsterdam, Netherlands	2019	Under construction	Plastic waste	Marine diesel oil (low sulphur)	371[5] (35 000)	n/a		36, 82, 83
IGE (UK)	IGE UK (3 plants)	United Kingdom	?	Planned	Plastic waste	Not specified[6]	3*707 (3*70 000)	n/a		36, 82, 83
IGE (USA)	IGE Indiana	Camden (Indiana), USA	?	Planned	Plastic waste	Not specified[6]	5 305 (525 000)	n/a		82, 83
ReNew ELP (UK)	ReNew Teesside	Teesside, UK	2019	Planned	Plastic waste	Not specified[7]	169 (15 900)[8]	n/a		89-91

Cassandra Oil/Valoriza[9] (Spain)	Valoriza Jerez	Jerez, Spain	?	Planned	Plastic waste	Synthetic crude[10]	509 (48 000)[8]	n/a		92, 93

[1] Assuming produced fuel is diesel only. Product split is not clearly specified.
[2] Calculated from feed rate and fuel product yield available in [33].
[3] Previously PK Clean.
[4] Production level is not specified by Renewlogy, but plastic feed rate equals that of the Nova Scotia plant.
[5] Assuming LHV 38.2 MJ/l
[6] The UK plants are claimed to produce "road-ready fuels" (https://www.foygroup.com.au/wp-content/uploads/2017-03-March-17-Quarterly.pdf). The capacity calculations (GWh) assume diesel for road use. The US plant is assumed to produce the same fuel as the UK plants.
[7] The technology is claimed to give a synthetic crude that is miscible with conventional crude oil (https://renewelp.co.uk/process/). The intended end-use of the product of the planned plant is not specified.
[8] Calculations assume LHV 38.2 MJ/l, rho=1 kg/l and use the conversion rate (product/feed) claimed by the company.
[9] the Company already has operations on-site but does not clearly specify to what extent. Operations began in 2014 with a testing phase. After testing, a processing capacity of 24 000 t/year of plastics was expected by 2015 https://futurenviro.es/en/valoriza-pone-en-marcha-la-primera-fase-de-la-planta-de-valorizacion-de-residuos-plasticos-en-jerez-de-la-frontera-cadiz-2/ Very little information on production levels has been communicated by the company in press releases, but there is no indication that large scale production has been reached. When the project plans listed in this table were announced, present activities on-site were described as technology tests only http://www.cassandraoil.com/sv/Press/Pressmeddelanden/Pressmeddelande/?releaseid=2361867.
[10] Quality sufficient for use as refinery feedstock (http://cassandraoil.com/sv/Press/Pressmeddelanden/Pressmeddelande/?releaseid=2070417)

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